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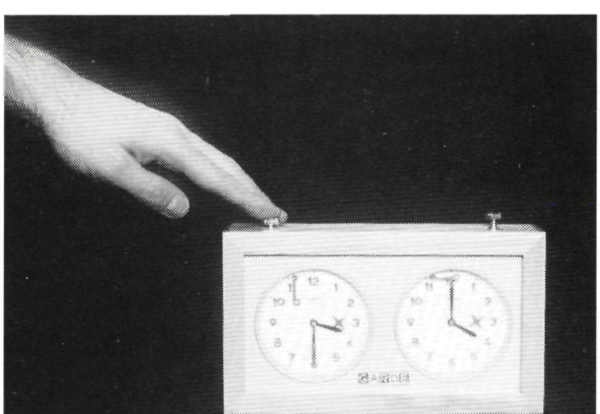
MENTAL SPEED AND CONCENTRATION

a mathematical model approach



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MENTAL SPEED AND CONCENTRATION

A MATHEMATICAL MODEL APPROACH

Mentale snelheid en concentratie

een wiskundige model benadering

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MENTAL SPEED AND CONCENTRATION

A MATHEMATICAL MODEL APPROACH

een wetenschappelijke proeve
op het gebied van de sociale wetenschappen,
in het bijzonder de psychologie

Proefschrift

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Voorwoord

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Contents

1 INTRODUCTION

The first chapter of this thesis provides an outline of the domain of interest. The duration of mental processes is a central issue, but it is treated in another way than usual in experimental psychology. It is assumed that the observed reaction time contains partly time wasted on task irrelevant mental activities, which is called distraction time. The inhibition theory deals with both processing and distraction time. The theory is introduced in this chapter. Further, the similarities and differences of psychometrics, experimental psychology and mathematical psychology are described. Finally, the goals of this thesis are summarized and an overview is given of the contents of the subsequent chapters.

1.1 Domain of interest

> [...] *the assumption that the observed RT can be considered to be an adequate measure of the duration of underlying mental processes is not only readily accepted within psychometrics but also in practically all RT models used within the realm of experimental psychology. Within the realm of psychometrics there is one notable exception, viz. the study of Peak and Boring (1926). In discussing their experimental data, Peak and Boring suggest two alternative explanations for the finding that the RTs of two subjects solving the same items differ. First, the difference may arise because the slower subject, while executing the necessary operations at the same speed as the fast subject, loses time by what they call 'irrelevant activities' or 'self distraction'. Alternatively the difference may arise because both subjects execute the necessary operations at a different level of speed.*

This quotation from Pieters (1984, p.5) contains almost all elements of interest to this thesis: (1) the concepts of mental speed and of distraction, which is time spent on irrelevant mental activities, (2) the measurement of the durations of mental processes, and (3) the different approaches of psychometrics and experimental psychology. Each of these three topics will be previewed in this chapter.

At the core of it all stands the reaction time (RT) performance on mental tasks. The observed RT can be considered to be either an unbiased reflection of the duration of mental processes or a biased measure of it. In this second case the RT needs to be split into time spent on solving the task and time devoted to task irrelevant activities. These two positions of treating the observed RT as either an unbiased or a biased measure of mental processes should be distinguished throughout this thesis. Whereas Peak and Boring (1926) conclude from their study that time wasted to irrelevant activities is negligible in the RTs of their subjects, the present thesis shows that given certain tasks and conditions the amount of distraction time cannot be ignored.

The three points that mark the domain of interest of this thesis, can be viewed as the three layers of scientific research: (1) the observation, (2) the theory, and (3) the meta-theoretical position.

The notion of time spent on irrelevant mental activities (which we call distraction time) is based upon the observations that (a) subjects are unable to keep up a good level of performance over a longer period of time, and that (b) subjects differ in their ability to concentrate or to sustain attention over a certain period of time. In the next chapter an extensive review is given of the experimental observations of RT performance on simple repetitive mental tasks during the past century. In chapter 6 individual differences in concentration will be considered.

Assuming that the observed RT contains distraction time, a theory should be developed which incorporates distraction time and which is able to predict a decline in RT performance with time on task. The inhibition theory satisfies these requirements. An introduction of this theory will be presented in the sequel.

The inhibition theory is formalized into a mathematical model. This enables us to predict the expected RT, E(RT), on each trial of each subject given that his model parameters are known. This approach of RT analysis is uncommon in at least two ways. First, a mathematical model approach is still not frequently employed, since most researchers are unwilling to pose very specific and restrictive assumptions. Secondly, in most RT analyses the processing time is partitioned into the durations of more elementary processing stages, whereas the inhibition theory deals only with the total processing time. Instead of the model approach most RT analyses within experimental psychology employ either the Additive Factor Method or the

Subtraction Method to discover processing stages or to measure the durations of these processing stages. In section 1.3 a short review is given of the methods commonly used to measure the durations of mental processes.

From the perspective of a broader framework, the research approach of this thesis belongs to the field of mathematical psychology. The kind of progress made within scientific research depends at least partly (and perhaps even foremost) on the scientific approach chosen. The scientific approach determines how to construct the theories, how to derive the predictions, and how to design the experiments. Within psychology three different approaches can be distinguished: (1) psychometrics or test psychology, (2) experimental psychology, and (3) mathematical psychology. In section 1.4 these approaches will be further introduced.

1.2 The Inhibition theory: an Introduction

The main issue of this thesis deals with the relation between the mental processing time and the total RT. The basic assumption is that the total RT contains more than just the time for processing the task at hand. This difference in time between total RT and mental processing time is called distraction time, i.e. time devoted to task irrelevant mental activities. From this point of view every RT analysis intending to measure the duration of mental processes is biased unless distraction time is experimentally controlled for, or computationally adjusted.

The inefficiency of mental processing is the main issue in the development of the inhibition theory, as distraction time is in fact nothing else but wasted time. One way in which the inefficiency of mental processing is observed, is with prolonged mental performance. In the next chapter it will be shown that performance declines with time on task. This decrement is found for different variables, such as RT, error rate, and sensitivity of detection, on various mental tasks, such as serial RT tasks, vigilance tasks, tracking tasks, and repetitive choice RT tasks. The inhibition theory is one of the few theories which explicitly predicts a decrement in RT performance with time on task.

In its essence, the inhibition theory comes down to two propositions: (1) a RT contains processing time and distraction time, and (2) the tendency to shift from processing to distraction increases with the accumulated processing time and decreases with the accumulated distraction time. These two propositions predict that the amount of distraction time will be low at the start of a task and that it will increase as a subject is continuously at work.

Another way in which the inefficiency of mental processing can be observed, is in individual differences of concentration. Within the inhibition theory concentration can be defined as the ratio of processing time and distraction time. In chapter 6 a specific measure of concentration, which logically follows from the inhibition theory, is proposed and tested in some applied settings.

Throughout this thesis the model approach of RT analysis is chosen. The basic assumption of all the presented models is that RT is the sum of the processing time and distraction time. Van der Ven and Pieters (Van der Ven & Pieters, 1977; Pieters & Van der Ven, 1982) started the present line of research with the presentation of the Poisson-Erlang (PE) model. The successor of the PE-model is the INHIBITION model developed by Van der Ven and Smit (Van der Ven, Smit & Jansen, 1989). Whereas it is assumed in the PE-model that the expected distraction time is the same for every trial, the INHIBITION model assumes that the expected distraction time increases during a sequence of trials until some stationary level of distraction time is reached. Both models assume that the processing time is constant. These assumptions imply that the PE-model predicts a stationary RT over consecutive trials, whereas the INHIBITION model predicts an increasing RT over a series of trials, which becomes stationary after a certain number of trials. The mathematical details of these models will be discussed in chapter 3.

1.3 Some methods for assessing processing time

Saul Sternberg (1969a) can be credited for the renewed interest in the decomposition of RT into the durations of some elementary mental processes. Donders (1868/1969) could be called the founding father of this tradition of the measurement of speed of mental processes. The revolutionary work of these two researchers will be briefly reported in the sequel. First, a framework of the RT analysis will be given as proposed by Sternberg (1969a).

Most RT analyses assume that there are successive functional stages between stimulus and response whose durations are additive components of the RT. A stronger assumption added sometimes to the first one is that these RT-components are stochastically independent. Finally, in a few cases a complete specification is given of the forms of the distributions of the RT-components.

The first assumption implies that the mean RT is the sum of the means of the components. For instance, knowing that two different processing stages exist, the mean RT is the sum of the means of the durations of these two processing stages plus the mean of the duration of all other events between the stimulus and the response.

The stochastical independence of the RT-components has strong implications. Not only are the component variances assumed to be additive but also all higher cumulants are assumed to be additive as well. One of the implications that follow from these assumptions, is that the duration of a RT-component has no influence on the duration of the next RT-component.

By specifying the distributions of the RT-components, one can deduce the RT distribution itself. In practice, the observed RT distribution should be the key to the underlying processes. By mathematical deductions or by simulations it is then often possible to decide which RT-components determine the RT distribution most. An example of such a distributional or model approach is the decision model of Hohle (1967), which will be treated in a later section.

A complete specification of the durations of the underlying mental processes is the ultimate goal of every researcher in this field. Still, Sternberg (1969a, p.279) points out two major problems with this model approach:

> *One problem for an approach such as Hohle's, in which a strong model is invoked, is that when the model fails it is of course difficult to decide which of its several assumptions is at fault. A second problem is that rather different sets of components may give rise to RT distributions that have approximately the same form. There are several advantages, therefore, in testing relatively weaker models, or examining assumptions one at a time.*

Since the model approach is favored in our studies, we have to deal with these two problems throughout this thesis.

In the next three sections Donders' Subtraction Method, Sternberg's Additive Factor Method, and the model approach of RT analysis will be discussed.

1.3.1 Donders' Subtraction Method

The work of Donders (1868/1969) was based upon the idea that between stimulus and response a train of successive processes, or stages, is executed. Each component process begins only when the preceding one has ended. Donders developed the *Subtraction Method* to measure the duration of some of these stages. Mean RTs of two different tasks are compared, where one task is thought to require all the stages of the first, plus an additional stage. The difference in mean RT is taken to be an estimate of the mean duration of the isolated stage.

The first criticism of the Subtraction Method is that it begs a priori postulates concerning which stages play a role in an experimental task, while the objective is actually to infer stages (Sanders, 1980). Obviously, the conclusions reached on the basis of the application of this method can then be no stronger than the substantiation of the initial conceptualization of the task (Pachella, 1974).

A second major criticism is known as the postulate of pure insertion (Sternberg, 1969b; Ashby & Townsend, 1980; Pieters, 1984, 1985). Donders' method requires that two experimental tasks can differ on only one stage without altering the other stages. In order for differences in mean RT between the experimental and the comparison task to represent meaningfully the duration of an isolated process, all of the other processes common to both tasks have to be strictly comparable.

As Pachella (1974) rightly remarks, to the extent that the general criticisms can be levied against the Subtraction Method their conclusions must suffer. Still, several fruitful empirical results have been obtained by means of Donders' method (Taylor, 1966a; see also Smith, 1968).

1.3.2 The Additive Factor Method

Sternberg (1969a) proposed a method of testing for additive RT-components and of inferring the organization of the processing stages without requiring procedures that add or delete stages. The main differences between the Subtraction Method and the Additive Factor Method is that the latter method does not lead to the measurement of stage duration, but only to the discovery of processing stages. With the phrase 'discovery of processing stages' Sternberg meant testing the existence and independence of experimentally controlled processing stages.

Sternberg (1969a, p.281) explains his method as follows. Suppose that *a*, *b*, and *c* are among a series of stages between stimulus and response. Suppose further that there are three experimental factors, F,G, and H, such that factor F influences only the duration of stage *a*, factor G influences only the duration of stage *b*, and factor H influences stages *b* and *c*, but not *a* [1)] What are the most likely relations among the effects of the three factors on the mean RT? The general idea is that when factors influence no stages in common, their effects on mean RT will be independent and additive, because stage durations are additive. That is, the effect of one factor will not depend on the levels of the other factors. Thus, factors F and G should have additive effects on mean RT. On the other hand, when two factors, G and H, influence at least one stage in common (stage *b*) there is no reason to expect there effects on RT to add. The most likely relation is some sort of interaction.

The inferences from the data are based upon the reversed logic. If two variables have a main effect on RT, while their effects do not interact, two different processing stages are likely to be involved. Alternatively, if the effects interact, the variables are likely to affect at least one common processing stage, since the size of the effect of the one variable depends on the effect of the other.

Sanders (1980) described the state of the art in RT analysis a decennium after the appearance of Sternberg's publication. Sanders started with elaborating on the doubts raised against the Additive Factor Method. Two of the most relevant criticisms are those concerning the processing stages and the basic logic of the method.

Same as in the Subtraction Method, the assumption is made that most of the processing stages between two experimental task conditions are completely comparable with respect to duration and the end product of each stage. Within a task both methods assume that processing stages are serial and that the durations of the stages are additive. These assumptions are seriously questioned by theories dealing with reallocation of capacity from a common pool (Moray, 1967) or changes in the investment of effort (Kahneman, 1973).

The problem with the basic logic of the method is that the deduction *'if variables affect different processing stages, then their effects on RT add'* cannot be reversed to the induction *'if two*

[1)] By a factor Sternberg means an experimentally manipulated variable, or a set of two or more related treatments called 'levels'. The effect of a factor is the change in the response measure induced by a change in the level of that factor.

variables have additive effects they affect different processing stages' (Prinz, 1972; Sanders, 1980). Therefore, additive effects can only be interpreted tentatively in terms of different processing stages.

Yet, quite a number of processing stages have been inferred from additive effects in the experimental data since Sternberg's publication. For instance, in choice RT tasks Sanders (1980) proposed already six serial processing stages: (1) preprocessing, (2) feature extraction, (3) identification, (4) response choice, (5) response programming, and (6) motor adjustment. The discovery of processing stages can be credited to the Additive Factor Method, but at the same time the method can lead to the situation, in which each researcher has his own processing stages depending on the experiment he did.

1.3.3 The model approach to RT analysis

Pieters (1983, 1984) commented upon the work of Sternberg by referring to the distinction between a functionalist or stage analysis approach, and a structuralist or model approach. He states that the stage analysis approach poses the question: *Which variables have an effect, and do they interact?* whereas the model approach addresses the question: *What are the processes involved, and how do the variables affect these processes?* (Pieters, 1983, 1984; Theios, 1973). These two questions show the major differences between the two approaches. On the one hand the model approach tries to explain why certain experimental phenomena do occur, whereas the stage analysis approach only describes what variables may be involved. On the other hand the stage analysis makes less assumptions than the model approach that almost completely predicts the data.

An example of the model approach is the decision model of Hohle (1967). Hohle states that the main RT component is the decision process. His theory on the execution of mental tasks is, further, that the process between stimulus presentation and motor response consists of a large number of subprocesses of which decision is the most important. The duration of this decision process is assumed to have an exponential distribution with parameter τ, whereas the sum of the durations of all the other processes has a normal distribution with parameters μ and σ.

Such a model can be tested in two different ways. First, the predicted RTs of the model can be compared with the observed RTs by means of a goodness-of-fit test.

Secondly, the model parameters are expected to change in a certain direction due to experimental manipulations. The predicted effects on the model parameters can be tested. In this example of Hohle's Decision model experimental effects on parameter τ are expected due to manipulations of payoffs for speed versus precision, whereas the parameters μ and σ should be affected by stimulus quality or response modality. Hohle's Decision model was tested by Pieters (1985). His results suggested an acceptable fit, but failed to support predictions about experimental effects on the model parameters.

The PE-model and the INHIBITION model (see chapter 3 for details) belong to the class of the processing-distraction models. The first assumption of all the processing-distraction models is that RT is the sum of alternating processing and distraction periods. This class of models is central to this thesis. The specific assumptions and the empirical consequences of these assumptions are treated in chapter 3. Some specific empirical consequences are tested in the chapters 4 and 5.

1.4 Different perspectives in psychological research.

A traditional distinction in psychology is between psychometric research for the measurement of individual differences, and experimental research for the analysis of psychological processes in general. Rarely are the two combined. In using a mathematical model approach, however, the two objectives can be combined.

Psychometrics or test psychology. According to Nunnally (1978), psychometric theory deals foremost with measurement problems notably concerning individual differences. In general, psychometrics is mostly concerned with the development of proper rules for the quantification of psychological entities. Objectivity, reliability, and validity are some of the criteria to judge whether a measurement scale is an appropriate quantification of a psychological entity.

An example of the kind of research within psychometrics or test psychology is the measurement of intelligence. Employing factor analysis as its major tool, a large number of psychometricians have tried to grasp the concept of intelligence within a few 'intelligence' factors. As will be discussed in chapter 3 the outcomes of these scientific enterprises were quite diverse.

Less ambitious is, for instance, the measurement of reading skill. In this case, it is very well possible to formulate a certain criterion in order to test the validity of the instrument meant to measure reading skill. In most cases it is not difficult to obtain a high level of reliability for the desired measurement scale.

Experimental psychology. In a psychological experiment an organism (O), the subject, responds (R) to a stimulus (S). This general statement can be put into the form of an equation

$$R = f(S, O) \tag{1}$$

which reads that the response is a function of stimulus factors and organism factors (Woodworth & Schlosberg, 1953). The objective of experimental psychology is to assess the function that determines the responses by systematically varying the stimulus and organism factors.

Experimental psychology is characterized by the experimental method. Of major importance is the replicability of the observations in a particular condition. The central idea of the experimental method, however, is that one factor can be held responsible for the observed variation in the results, if all conditions are kept constant except for this one factor, the experimental variable.

Most of the research reported in chapter 2 belongs to the field of experimental psychology. The general observed phenomenon in those cases is the performance decrement with time on task. The general law which should hold for every subject, is that mental performance will become worse with prolonged work. The specification should be made that this law holds in case of a simple mental task administered on massed trials, i.e. with a very small response stimulus interval. A further specification is that the performance curve follows a decelerating function.

Psychometrics versus experimental psychology. Psychometrics is concerned with the measurement of a particular psychological variable. Experimental psychology aims at the discovery of relations between variables. For instance, the measurement of loneliness is a psychometric problem, whereas experimental psychology seeks to find causal relationships between loneliness and other variables, e.g. loneliness and hypothermia (Hypothermia means low body temperature, which is seen as a major death cause of the elderly during severe winter periods). A further difference between psychometrics and experimental psychology is that psychometricians aim at measuring individual differences, while experimental psychologists only want general laws applicable to each individual. An example is the measurement of mental speed, which is treated extensively in chapter 3. Individual differences on mental speed concern psychometricians with regard to intelligence testing. Experimental psychologists, however, would only be interested in questions like: *Is mental speed affected by amfetamine?* or *Will sleep deprivation slow down mental speed?*

Mathematical psychology. Mathematical psychology enables that individual differences as well as general laws can be considered within the same framework. For a particular class of psychological phenomena a theory is stated in terms of a formal model. When the model has been constructed, its consequences may be derived using the rules of logic and the available mathematical machinery (Coombs, Dawes & Tversky, 1970; Coombs, 1983).

For instance, the theory of Hohle (1967) on information processing was formalized into the Decision model. The consequences of his particular formalization was that the following equations hold for the expected RT and the $RT_{Variance}$ (see Pieters, 1985).

$$\begin{aligned} E(RT) &= \tau + \mu \\ Var(RT) &= \tau^2 + \sigma^2 \end{aligned} \qquad [2]$$

Given the parameter estimates predictions of condition effects on the parameters can be easily tested. Since the model parameters can be estimated for each individual, it is possible to take individual differences on the decision parameter τ into consideration. Within the realm of intelligence testing it might be of interest to correlate τ with some measure of general intelligence.

The present thesis belongs to the field of mathematical psychology. The importance of this field was excellently described by Coombs, Dawes, and Tversky (1970, p.4):

> *The advantage of mathematical models over other forms of theories lies in their generality, their precision, and their deductive power. By using the language of mathematics, psychological theories can often be stated in a form that is both general and precise. Moreover, by using logical derivations, the*

investigator can discover the consequences of his assumptions, some of which may not be apparent at all.

1.5 Goal setting and an overview

The aim of this enterprise is, first of all, testing the empirical value of the inhibition theory. In its most general form, this theory claims that performance decrement arises from continuous processing of a homogeneous task.

As an introduction to the experimental literature chapter 2 yields an overview of the research on inefficient mental processing. It is claimed that the inhibition theory is very well suited to explain inefficient processing on simple repetitive tasks. Two other theories in the specific domain of performance decrement with time on task are described and contrasted with the inhibition theory. A critical test of the different theories is given in chapter 5.

In chapter 3 the inhibition theory will be given full attention. Testing a theory can only be done by testing specific predictions deduced from the theory. The approach adhered in this thesis derives predictions from worked-out mathematical formalizations of the theory. Such a mathematical model is a very specific version of the general theory. It yields precise and restrictive predictions. Sometimes the predictions can be more restrictive or constraining than necessary for the theory. However, if these predictions hold the general theory is corroborated a fortiori. If the data fail to support the predictions, it is bad for the model, but not necessarily bad for the theory. This combination of theory and model is what is meant by *a mathematical model approach*. The distinctions and connections between theory and model is further elaborated in chapter 3. Showing the usefulness of the mathematical model approach could be called the second goal of this thesis.

Essentially, this thesis contributes to the field of cognitive experimental psychology. Therefore, a number of experimental studies will be reported. They all aim at testing the inhibition theory. Chapter 4 reports the test of the inhibition theory in the so-called massed versus spaced paradigm. In chapter 5 the homogeneous versus mixed paradigm is employed to supply additional empirical support for the inhibition theory. In chapter 6 an experiment is reported in which more and less different tasks were mixed. The combination of the inhibition theory and this mixed tasks condition might give a lead to the discovery of mental processors.

A third goal of this thesis is to use the inhibition theory for measuring individual differences. In particular, a practically feasible measure of concentration is developed. This measure follows logically from the inhibition theory. Chapter 8 deals with the measurement of concentration. Chapter 7, finally, contains an introduction to the measurement of individual differences, in particular to the measurement of mental speed.

2 RT PERFORMANCE ON REPETITIVE TASKS: A HISTORY

The endeavours of psychologists to investigate performance decrement with time on task is reviewed starting at the early years of the past century and ending in the present. Several explanations have been proposed in answer to the question why human subjects are incapable of keeping up good performance in a simple task over a relatively short period of time. Recently, another explanation derived from the inhibition theory was added. A summary of the explanations is given, but an evaluation is postponed until later chapters.

Reaction time (RT) performance on repetitive tasks has been a subject of investigation on numerous occasions. The effects found in these experiments are fairly consistent. An impairment in performance is usually observed with time on task. Although this effect has been established throughout the history of psychology, no satisfactory explanation has been convincingly put forward. In this chapter a review will be given of a bulk of research in this specific field. In addition, the explanations proposed for the decrement in continuous RT performance will be treated shortly. In the final chapter of this thesis these explanations are evaluated against some diverse experimental results. It turns out that the inhibition mechanism presented in this thesis seems most appropriate in dealing with the problem of the generally observed performance decrement with time on task.

2.1 The observed effects

2.1.1 Bessel, Helmholtz, Donders (1820 till 1900)

RT as a performance measure started accidently at the beginning of the 19th century. In 1822 a German astronomer, Bessel, noticed systematic discrepancies in recorded times of the passage of stars across the meridian held. Bessel and later Helmholtz found this individual deviation in recording the time transit an important source of error, and it became known as the *Personal Equation*. The easiest explanation of the fact seemed to be that one individual reacted more quickly than another because his nerves conducted more quickly.

Helmholtz investigated the complete circuit from the stimulation of a (human) sense organ to the motor response. By varying the point of stimulation he sought to ascertain variations in reaction time which would throw light on the speed of conduction in sensory nerves. These were the earliest 'reaction time' experiments as such (see Murphy & Kovach, 1972).

It was not Helmholtz, but Donders (1868/1969), a Dutch physiologist, who grasped the psychological significance of the problem. He realized the importance of some psychological factors intervening between stimulus and response. Although Donders was not a psychologist, he contributed greatly to subsequent psychology when he hypothesized that reaction time could be used to estimate the speed of internal cognitive processes. He developed the so-called *Subtraction Method*. The basic logic of this method is that the temporal duration of a single processing stage can be measured by comparing the time to solve one version of the task, which includes that processing stage, with a second version of the task that differs from the first task only by the deletion of that processing stage. The difference in solution time for the two versions of the task represents the time spent on the processing stage of interest. In principle, successive deletion can be used in order to obtain an estimate of the duration of each processing stage. As was explained in first chapter, the major objection against the Subtraction Method is the assumption that the execution of a task can differ on the execution of only one processing stage. Despite this criticism there is some renewed interest in the work of Donders (see Ashby & Townsend, 1980).

For further reading on the topic of the start of the RT paradigm see Woodworth and Schlosberg (1953), Murphy and Kovach (1972), Lachman, Lachman, and Butterfield (1979), or Eysenck (1984).

2.1.2 Kraepelin, Bourdon (1900 till 1920)

Most of the following remarks on the work of Kraepelin and his students stem from Eysenck and Frith (1977). They focused primarily on the effect of reminiscence, whereas the present study deals foremost with work decrement.

Kraepelin. Kraepelin (1902) considered that prolonged work, whether muscular, as on the dynamometer, or mental, as in adding single digit figures, produced certain effects, such as fatigue, and was in turn affected by certain variables, such as motivation. These variables and effects were a function, in part, of the personality, normal or abnormal, of the experimental subject, and could in turn be used to throw some light on aspects of the personality. Hence the efforts for his subjects to complete series of digit additions that lasted several hours and the efforts for himself to analyze these data were just one important method of gaining a better understanding of the dynamics of behavior, and of individual differences. He was aware of the fact that a better understanding of fatigue, motivation, set, reminiscence, and learning might have far-reaching practical consequences in the clinic, the classroom, and in industry, but he did not personally concern himself very much with the application of his work. His concern was first and foremost the clarification of the scientific and academic problems.

The first study which is relevant to our topic of work decrement is one published by Oehrn (1895). He used a variety of tasks including letter counting, letter search, proof reading, nonsense syllable learning, number learning, various motor functions such as writing, and finally the one most important from our point of view, addition of single numbers in Kraepelin's *Rechenheft*, timed over consecutive 5 minute periods. Work continued over periods of two to four hours. Oehrn as well as Kraepelin believed that practice and fatigue are the two most important influences that determine the major portion of an individual's performance at any one point. Fatigue is conceived as partly a physiological effect, but also as a decline in attention.

One of the results Oehrn (1895) obtained was that rest pauses (of 24 hours or more) allow fatigue to dissipate, while the effects of practice remain. Oehrn also observed marked fluctuations of speed in adding single numbers, although the dependent variable was the mean RT over 5 minute periods of work. This variability, which is a function of the number and size of the fluctuations observed, was considered by Oehrn to be a measure of attention. He supported this notion by showing that simpler, more reflex types of task showed less variability.

Von Voss (1899) made a more analytic investigation of the fluctuations of performance. He measured the length of single additions in milliseconds. Per 5 minutes work periods he classified the RTs into five categories, namely 400-600 msecs, 600-800 msecs, 800-1000 msecs, 1000-1200 msecs, and 1200 or more milliseconds. Most of the RTs fell between 600 and 800 milliseconds. Nevertheless about 10 percent of the RT data were over 1200 msecs. Von Voss registered the prolonged work for a full hour. So he had 12 consecutive periods of 5 minutes. Whereas the frequencies of the fast RTs were about the same for the first and the last 5 minute work periods, the percentages of the longer RTs were larger in the last 5 minute periods. These long addition times correspond to what Bills was much later to call 'mental blocks' (Bills, 1931). The observation that longer RTs are more frequent in the last work periods are in line with the research of e.g. Bertelson and Joffe (1963). According to von Voss the cause of the fluctuations in attention is to be found in central mechanisms, not in peripheral ones.

Hylan and Kraepelin (1904) took up the investigation of massed and spaced (i.e. work with intervening rest pauses) practice, and the effects of different lengths of rest pause using also the addition task with consecutive 5 minute work periods. They found that on the whole improvement of performance was a direct function of duration of rest pause, at least up till half an hour of rest, which was the largest rest pause used. According to Hylan and Kraepelin dissipation of inhibition (mental fatigue) during rest is a function of the length of the rest pause and of the duration of the pre-rest practice. This notion which dates from the beginning of this century, is (although for other reasons) only recently formalized into a mathematical model for the measurement of speed and concentration (Van der Ven, Smit & Jansen, 1989; see also Van Breukelen et al., 1987b).

Pauli (1938,1939) turned the prolonged work task of successive additions into a test to account for the individual differences in what we would call today sustained attention. Nowadays 'die Arbeitskurve' (the performance curve) of successive adding is examined using the Pauli-test (see Arnold, 1975).

Bourdon [2)] It was Oehrn (1889,1895), one of Kraepelin's students, who was the first investigator using a cancellation task. The subjects in his study had to mark specific characters in a reading task. In this way Oehrn intended to investigate the speed of perception.

These cancellation tests are nowadays associated with the name Bourdon. Bourdon (1895), a Belgian psychologist, designed his first cancellation test (crossing out the character ' *a*' while reading a text) to investigate recognition, discrimination and association. A few years later Aikens, Thorndike and Hubbell (1902) concluded that the cancellation test is more suited to measure attention than discrimination.

Referring to Abelson (1911) and his tutor Wiersma, Godefroy (1915) introduced the so-called Bourdon-Wiersma test. In this pencil-and-paper test a number of dot patterns are administered to the testee, who is instructed to cross out all patterns with four dots. Only patterns with three, four, or five dots are included in the test. Per line of stimuli the RT and the number of failures are registered. Godefroy intended to measure fluctuations in attention. He used this test as a diagnostic

[2)] This passage relies heavily on a review of the Bourdon test by Kamphuis (1962).

instrument to discriminate between epileptic patients, patients suffering from dementia praecox or hysteria, and normal testees. Especially the epileptic patients showed up large fluctuations in RTs per line, which Godefroy interpreted as large fluctuations in attention. Up till today the Bourdon-Wiersma test is generally applied as a diagnostic instrument, at least in the clinics in the Netherlands (see e.g. Boeke, 1963, or Vos, 1988).

2.1.3 *Robinson, Bills (1920 till 1940)*

For the present purpose the interesting research starts with Edward Robinson and Arthur Bills (Robinson, 1920; Robinson & Bills, 1926; Bills, 1931, 1935a, 1935b). To them the work decrement was one of the major phenomena of psychology. In the same vein as the present study they investigated the principles underlying the losses in efficiency from relatively continuous work.

One of the experimental effects that they found was that heterogeneous work is much more resistant to the decrement effect than homogeneous work (Robinson & Bills, 1926). They selected a number of tasks differing from one another mainly in homogeneity of the stimuli and compared the magnitudes of the decrements associated with continued work at these several tasks. It appeared that their subjects found it much easier to write a six-letter sequence like *abcdefabcdef,* than a three-letter sequence like *abcabc,* or a two-letter sequence like *abab.* Moreover, it showed that this difference in decrement can be obtained from activities of the same or of similar initial efficiency. The same kind of results were also found for a letter-naming task. It should be added that these authors made a distinction between monotony and homogeneity. Monotony they thought was the subjective or affective nature of a homogeneous task.

They also investigated a factor antagonistic to heterogeneity. This factor was called competition. Competition between elements of the stimulus enlarges the work decrement. For example, in a color naming task the decline in responses per minute was largest in the condition with the largest number of different colors to name (Bills, 1935a). Nowadays this factor would most probably be called 'memory load'. For the moment we will stick to the term competition as proposed by Robinson and Bills (1926).

Bills became well-known by the introduction of the concept of *Mental Blocks* (Bills, 1931). In the RT performance on a continuous task mental blocks are defined as those RTs that exceed the limit of two times the mean RT of that series. These mental blocks emerged in such simple tasks as color-naming, code substitution, addition, naming opposites, and the like. They occured about three times a minute. Administering intervening rest pauses (spaced work) resulted in the almost complete disappearance of the blocks from the subjects' records. It was concluded by Bills that the artificial pauses fulfilled the same function as the natural ones, and therefore removed the need of blocks as rests (Bills, 1935a).

These factors, i.e. homogeneity vs. heterogeneity, massed vs. spaced work, and competition (mental load), will again be discussed in connection with the inhibition theory presented in this paper. Their experiments which were conducted in the twenties and the thirties will show to have a remarkable vividness in the light of our theory and experiments.

2.1.4 Pavlov, Hull (1940 till 1960)

Pavlov (1927) made much use of the concept of inhibition. He distinguished 'external' form 'internal' inhibition. The interference of one activity with another was external inhibition, while internal inhibition developed in a nerve center through its own activity. Fatigue might be considered an example of internal inhibition, but the examples that Pavlov had in mind were different from fatigue. He was thinking of extinction and of the delayed conditioned reflex.

Woodworth and Schlosberg (1953) described the animal experiments of Pavlov (1927) in the following way. The feeding center was thrown into the state of excitation by food in the mouth and even by the sound of a metronome after conditioning. Hence, the salivary conditioned reflex follows. But the conditioned stimulus also produced central inhibition which was dissipating rather rapidly, but which could build up to a considerable amount in a series of trials. When the omission of reinforcement cut off the major source of excitation, the continued repetition of the conditional stimulus threw the advantage to inhibition and resulted in extinction of the conditioned reflex.

Hull (1929, 1943) stripped Pavlov's concepts of physiological implications and used them as constructs in a purely behavioral sense. Hull's 'reactive inhibition' has behavioral properties like those of Pavlov's 'internal inhibition', in that it nullifies excitation, accumulates with repetition of a conditioned reflex, but dissipates rapidly.

Internal or reactive inhibition, according to the general definition, should occur even when the conditioned reflex is reinforced. With a fairly long time allowed between the trials for the inhibition to dissipate, the performance could improve rapidly, but with massed trials this would not occur because of the accumulation of inhibition. According to this theory, the more work per trial, and the less time between trials, the greater should be the inhibition. These predictions were checked and supported in relative simple animal experiments (Thompson, 1944; Montgomery, 1951; see Woodworth & Schlosberg, 1953, pp.670-674, for a review).

Whereas Pavlov's internal inhibition was assumed to have a physiological basis for any mental act, reactive inhibition might be called motor satiation; more specifically it is satiation for a particular movement. Woodworth and Schlosberg (1953) pointed out that the refractory period could not account for reactive inhibition, since an inhibition can last for 20 seconds or more, and that fatigue is no better as an explanation, for the few repetitions that can generate some reactive inhibition would be apt to produce warming up rather than fatigue. These same remarks can be made not only for motor activities, but also for mental activities as was shown in the work of Robinson and Bills (1926) and as was recently shown in the work of Van Breukelen and Jansen (1987a; Van Breukelen et al., 1987b; Jansen & Roskam, 1989). Glanzer (1953) also showed that stimulus satiation is an equally important factor for reactive inhibition as is motor satiation.

The fact that Pavlov and Hull dealt with learning theories supported by evidence mainly of experiments with animals, should be stressed. So, the concept of inhibition emerged from theories on learning. The paradigm of learning was abandoned in the later research on inhibition (see Mackworth, 1969; or Van der Ven, Smit, & Jansen, 1989). As for the experimental evidence, studies based on Hull's theory used human subjects already in the forties and the early fifties (Kimble, 1949, 1952; Bilodeau, 1952; Kimble & Shatel, 1952). These experiments supplied evidence on the issue of massed versus spaced practice. It was hypothesized that massed practice suffered from the accumulation of reactive inhibition, and that, therefore, spaced practice would be superior to massed practice. The results consistently supported this hypothesis. For further information on Hull's contribution to learning and inhibition the reader is referred to the work of Amsel and Rashotte (1984) and that of Kimble (1985).

2.1.5 Bills, Bertelson, Sanders (1960 till 1970)

In the early sixties the research on mental blocks gets a second chance. Bills himself publishes again on mental blocks and its application to various groups of psychiatric patients (Bills, 1964). More important than the results of this specific study was his summary of the preceding decades:

> *For several years, the author (1931,1935) has made laboratory studies of serial reaction time in continuous homogeneous tasks to determine how the normal brain functions from instant to instant in prolonged work sessions. Contrary to the conclusions of previous investigators, from Kraepelin on, that the characteristic change is a gradual increase in response latency known as a "general decrement" in output per unit of time, it was found that the modal reaction time tended to remain constant. The erroneous impression of a gradually increasing response latency resulted from using too gross units of output, such as responses-per-five-minutes, thus lumping together RTs of very different lengths and concealing the fact that runs of modal length RTs are interspersed with a single or a few RTs of prolonged latency, the overall effect being to produce a rough periodicity. These prolonged latencies were called "blocks", and were found to increase in length and frequency during a prolonged work session, but to decrease as a result of practice in the task.*
>
> *Pursuing the hypothesis that the blocks are brief involuntary rest pauses, necessitated by the accumulation of fatigue, or "reactive inhibition", to use Clark Hull's term, the author tested the effect introducing periodic enforced rests of a comparable length and frequency to the spontaneous ones of the subjects. The result was a considerable reduction in the frequency and occurrence of blocks.*

Foley and Humphries (1962) carried out two experiments using simple serial reaction tasks in the visual and auditory modalities, in an attempt to elucidate the underlying principles involved in blocking. No increase in the number of blocks was observed. They concluded that no evidence of any correlation between blocking and simple fatigue or inhibition was available. However, the stimuli they used were administered at a fixed pace of either four or eight seconds. If as commonly assumed the inhibition dissipates rapidly, then no increase in the number of blocks should be expected.

In an excellent paper Bertelson and Joffe (1963) analyzed the data of an experiment with a serial responding task to throw light on some issues connected with the 'blocking' phenomenon. The task consisted of pushing one of four keys in response to the appearance of four figures on a numerical indicator. It was self-paced. Thirty-five subjects worked on it uninterruptedly for 30 minutes. They showed that:

1. The main change which occurs in the distribution of reaction times during the session is the appearance of a tail of long times: this is in agreement with the blocking hypothesis, i.e. with the hypothesis that an extra delay is sometimes added to the normal RT.
2. The increase in number of long RTs takes place in the first five minutes of work.
3. Long RTs are preceded by an increase in mean RT and in percentage of errors, which take place over four or five preceding responses, and are followed by a return of both variables to normal level; this is in agreement with the hypothesis that blocks allow mental fatigue (inhibition) to dissipate.

Especially this last conclusion is very important, since Bills too easily gave blocks the explicit function of reduction of mental fatigue. If blocks genuinely have that function, then the RTs before the blocks should increase and after the block the RTs should return to their normal level. This was exactly what Bertelson and Joffe found.

Methods of massed and spaced practice were used by Sanders and Hoogenboom (1970) to study the effect of continuous work on human performance. They found a remarkable increase in RT over time-at-work only for the longer RTs in the massed condition, which is the continuous work condition. In the spaced condition with the intermittently administered rest periods no increase was found in the longer RTs. Moreover, the RTs in the spaced condition were always smaller than in the massed condition. As they concluded, it is tempting to explain the effect of the longer RTs by assuming the occurrence of occasionally high peaked noise, which becomes more frequent after a short initial period.

2.1.6 Mackworth, Parasuraman (1970 till 1990)

At the beginning of the seventies the interest in the subject of performance decrement was submitted into globally two diverse fields of research: (1) vigilance and sustained attention, and (2) monotony and boredom. Monotony and boredom are only treated very shortly, since the impairment referred to in that literature falls a bit beyond the scope of this study.

The vigilance task was originally designed to simulate a watch-keeping task (see N.Mackworth, 1950). It presented a highly irregular series of 'wanted' signals, which were slightly changes in a regular series of 'unwanted' or background events. The operator was isolated as far as possible from all other environmental stimulus variability, and received no information about his performance. Under these circumstances, a rapid decrease in the probability that a signal would be detected was found between the first and second half-hour of the task. Besides a decline in sensitivity of detection, an increase in the latency of the detection is usually found. These kinds of decrements in performance are relevant for the present purpose.

Monotony and Boredom. Davies, Shackleton and Parasuraman (1983) reviewed the literature on monotony and boredom starting with the remark that a common definition of these terms lacks. These terms are, however, frequently encountered in the literature on ergonomics. They are relevant to situations in which people have to execute the same kind of operations for hours and hours, but also to tasks of a repetitive nature in the laboratory. In such monotonous and boring situations an impairment in performance is always observed.

Baschera and Grandjean (1979) drew a distinction between monotony and fatigue, associating monotony with underload and fatigue with overload. According to these authors the states of monotony and fatigue have in common that both produce impairment of performance and feelings of fatigue and sleepiness. A difference is that monotony is quickly reversible, while fatigue requires an adequate recovery period. They conclude from their experiments that repetitive tasks with a low degree of difficulty produce a state of monotony due to the lack of stimulation, whereas a repetitive task with a high degree of difficulty produces a state of fatigue due to a high mental load.

The concepts of monotony and boredom are commonly used in applied psychology. O'Hanlon (1981) concludes from a review of this literature:

Deficient performance has often been observed in monotonous tasks that continue without interruption for an hour or more. When those tasks involved repetitive motoric activity, the impairment took the form of occasional slow reactions that either increased output variability or led to timing errors. The latter were identified as a cause of industrial accidents (Branton, 1970). Tracking performance deteriorated during continuous manual control tasks, particularly when the operator's visual stimulation was limited to that providing the information required for completing the task. Part of this impairment was attributed to transient attentional lapses causing interruptions in the operator's motoric output. Finally, fault or target detection performance was found to deteriorate over time on task, or to remain stable at a low level of efficiency, in more than a dozen realistic versions of inspection on monitoring tasks. All types of decrement were reversed by short pauses in the working regimen.

The kind of performance decrement referred to in this chapter results mostly from work lasting at most one hour, whereas in the applied settings, as mentioned by O'Hanlon (1981), the work decrement usually involves a period of work of at least a couple of hours. Therefore, the literature on applied psychology is not further considered and only the literature on vigilance and sustained attention is dealt with at this place. Note, however, the striking resemblance in the kind of deficient performance between the long lasting monotonous task setting of the factory and the short term homogeneous[3] task setting of the laboratory.

[3] In the sequel we will use the word homogeneous instead of monotonous to indicate the task situation in which stimuli of a certain kind are repetitively presented. The word monotonous has too much the connotation of a boring situation, which already implies some cognitive process. However, this cognitive process is the subject of investigation.

Vigilance and Habituation. Jane Mackworth was about the last exponent of those who regarded the impairment of repetitive task performance as a general psychological phenomenon. Although she was mostly interested in behavior on vigilance tasks, she did not neglect to combine experimental effects on all repetitive tasks in her effort to explain the decline in performance. Most of the material on this topic of vigilance and habituation comes from her book of 1969 bearing just that same title.

Mackworth (1969) showed that a decrement in performance, expressed as changes in sensitivity, criterion, speed or accuracy, may be found in a very wide variety of tasks, such as tracking tasks, reaction time tasks, and other homogeneous tasks. In each case the changes appear to be related to the square root of time on task (see Taylor,1966b). This means that the fall of performance is large at the start and that this decline in performance becomes less with time on task. The vigilance decrement may be a particular example of a wide-spread phenomenon involving decrease of neural reactivity to continued or repetitive stimulation. Such a decrease is regarded as a particular example of habituation of physiological responses. Changes in physiological measures attributed to habituation may also follow a negatively accelerated course, but the available data are very variable.

Habituation is a decline in innate responses due to repetition of the stimulus (see Thompson & Spencer, 1966). For example, habituation of the orienting response includes changes that may decrease the sensitivity of the organism to a stimulus as well as its readiness to respond. This decrease in sensitivity results not only from peripheral changes but also from changes in the central nervous system. The spontaneous rhythms increase, so that the incoming signals are less distinguishable from the neural noise. Several features of habituation of physiological responses have also been found in vigilance tasks, such as the exponential decay of the measure of sensitivity (d') and of the measure of the criterial level (β).

Starting from this concept of habituation, Mackworth (1969, pp.105-106) proposed the following theory to explain performance decrement in prolonged work.

> *In the normal subject, habituation may occur as a result of a cortical process, which constructs a model of the incoming stimuli, and then compares new stimuli with this model. If the new stimulus agrees with the model in all features, including temporal occurrence, then the neural response to the stimulus*

> *may be inhibited. The generalized response will be inhibited first, and later the specific cortical response, as well as peripheral responses.*

The same kind of ideas are well-known from Pribram (1967) and Sokolov (1963).

She continues with:

> *Habituation may result from an increase in the normal self- or recurrent inhibition by which a nerve damps down its own response. This process may be mediated by the frontolimbic system, and may be the mechanism for Pavlov's (1927) internal inhibition. Eysenck (1963) has given it the name of stimulus-produced inhibition, since it results from a repetition of the stimulus. He has suggested that this inhibition occurs more rapidly in extroverts, who are more dependent on the environment for arousal than are introverts.*

To clarify this theory of Mackworth the concept of habituation must be further examined. Habituation depends on repetition of a stimulus or series of stimuli, and therefore may occur in any situation in which a limited range of stimuli is presented repetitively. It will affect performance in those situations in which the limitation of performance is set by the readiness to detect and respond to a simple stimulus.

There are also a number of situation in which habituation is not expected to occur. For instance, it will not occur in situations in which attention can be relaxed and then returned to the task when an alerting stimulus occurs, as in the usual signal detectability tasks. It will also be masked in situations in which performance is limited by skill or mental processes such as coding or memory. Thus, for instance, a complex task in which the speed of response is reduced by a difficult decision is unlikely to show the effects of habituation.

Seemingly in contradiction with this last remark the decrement in performance is also observed in a fairly complicated tracking task. In this case, however, it is necessary that the task be well-learned before a decrement is seen. A hidden decrement may, nevertheless, be observed by improvement between the end of one trial and the beginning of the next (reminiscence, see Eysenck & Frith, 1977). The similarity of the rate of change in accuracy between vigilance tasks and tracking tasks suggests a similarity in mechanism. As with habituation, the decrement is approximately negatively exponential.

Taylor (1966b), summarizing a number of experiments, has pointed out that changes that are related to the square root of time can be found in a wide variety of perceptual tasks. He argued that for matters of efficiency, the portion of the perceiving mechanism that is allocated to a redundant input should be reduced, allowing greater capacity for other purposes. This idea of Taylor is similar to those of Pribram (1967), Sokolov (1963), and Mackworth (1969). A stimulus which is already known to the observer is paid less attention to.

In conclusion, a decelerating performance curve is usually found in well-learned tasks in which performance is limited by the readiness to detect and respond to a simple signal. The tasks require continuous attention to a relatively repetitive situation. The ability to pay attention to a repetitive series of stimuli decrease as a result of habituation of neural responses.

Vigilance and Sustained Attention. For the present purpose the work of Parasuraman is of great importance. In a number of studies he investigated the factors governing sustained attention on vigilance tasks. He states that an understanding of the processes underlying the vigilance decrement is the major theoretical issue in research on vigilance (Parasuraman, 1986).

Nevertheless, Parasuraman (1984) is not satisfied with the theoretical solutions offered by a number of researchers in the past decades. He concludes (Parasuraman, 1984, p.263)

> *The interpretation of performance decrements over time has been a primary focus for the theories of vigilance. A number of such theories have been postulated, including ones based on constructs of arousal, expectancy, habituation, motivation, and inhibition. As recent reviews have pointed out, however (Davies & Parasuraman, 1982; Loeb & Alluisi, 1977; Parasuraman, 1983; Warm, 1977), none of the theories can account satisfactorily for all the results; and at least one source of conflicting evidence can be brought to bear against each theory.*

One year later Parasuraman (1985) presents a multifactorial theory regarding the performance decrement in tasks requiring sustained attention. This decrement concerns the detection speed, the sensitivity of detection, and the response criterion. Parasuraman claims that the type of vigilance task is an important factor in explaining the vigilance decrement. He distinguishes between high event-rate and low event-rate tasks, and between successive discrimination tasks and simultaneous discrimination tasks.

In successive-discrimination tasks, targets have to be distinguished from a nontarget reference represented in recent memory, because nontarget and target features are represented successively. In contrast, in simultaneous-discrimination tasks, target and nontarget features are provided within the same stimulus event. Parasuraman (1979) showed that a sensitivity decrement over time occurred only for the successive-discrimination vigilance tasks when the event rate was high (greater than 24 per minute). In low event-rate tasks, sensitivity remained stable, and the vigilance decrement was associated with an increase in response criterion over time.

The taxonomic analysis suggests a role for both target expectancy and capacity limitations in the explanation of vigilance decrement, depending on the type of vigilance task. Specifically, Parasuraman (1985) suggests a three-factor model of sustained attention. (1) The level of vigilance is proportional to the level of tonic arousal. (2) Changes in target expectancy account for performance changes in low event-rate tasks. (3) In high event-rate tasks in which target discrimination imposes a memory load the sensitivity decrement reflects a loss in attentional capacity over time, i.e. a "cost of time sharing" similar to that observed in the performance of dual tasks.

The sensitivity decrement found in high event-rate tasks is generally small, of the order 10% to 15% in d'. Although only one source is monitored in these tasks, Parasuraman suggests that a cost of time sharing the primary process (i.e. the vigilance) with other processing activities may develop with time on task. This cost can be described generally in terms of sharing a single task (visual or auditory) with other irrelevant "tasks" (distracting thoughts, environmental noises, etc.).

With the mean amplitude of the N1 component (see Callaway, 1973) of the auditory Event Related Potential (ERP) in a 10 minute block as the dependent variable Parasuraman (1985) reported an experiment meant to test the inhibition/habituation hypothesis of Mackworth (1969). He concluded that this theory of Mackworth was not suited to account for performance decrement in vigilance tasks.

In this experiment a high event-rate versus low event-rate condition was crossed with a passive (ignoring signals) versus active (detecting signals) condition. Parasuraman hypothesized that the sensitivity of detection as reflected by d' and N1 should decrease with time on task, and that this decrease should be steeper for the high event-rate conditions than for the low event-rate conditions. For the sensitivity measure d' and for N1 he found exactly what he had predicted.

Parasuraman, however, stated that testing the habituation theory of Mackworth implied that the decrease in N1 should also be steeper in the active condition than in the passive condition. This last prediction was not supported by the data. Therefore, Parasuraman concluded that the habituation theory could not account for vigilance decrement. The objections against this conclusion involve the facts that N1 is hard to measure, that the difference between 'passive condition' and 'active condition' is questionable, and that the (statistical) power to find a three-way interaction is very low. It should be added that Parasuraman did not test any of his predictions in this experiment statistically.

The conclusion to be drawn from this ERP experiment, however, could just as well be in favor of the habituation theory of Mackworth, if one points out that N1 decreased with time on task, and that this decrease was more severe in the high event-rate conditions than in the low event-rate conditions.

2.2 The theoretical positions

Several explanations have been proposed to solve the problem of a decline in performance on a repetitive task. The early researchers on this topic, such as Kraepelin, Oehrn, von Voss, Wiersma, Godefroy and others, all explained the fluctuations and the decline in performance on a repetitive task as fluctuations and a decline in attention. What they did was only attaching a label to some observed phenomena. An obvious question in this case remains unanswered: *What is (sustained) attention?*

Bills (1931, 1964) hypothesized that longer reaction times (mental blocks) contain brief involuntary rest pauses, necessitated by the accumulation of mental fatigue, or 'reactive inhibition' to use Hull's (1943) term. Reactive inhibition nullifies behavioral excitation, accumulates with repetition of a conditioned reflex, but dissipates rapidly. According to this theory, the more work per trial, and the less time between trials, the greater should be the inhibition.

Vigilance decrement was regarded by Mackworth (1969) as a particular example of habituation of physiological responses. Habituation is a decline in innate responses due to repetition of the stimulus. It results from an increase in the recurrent inhibition by which a nerve damps down its own response.

Parasuraman (1985) asserts that the sensitivity decrement reflects a loss in attentional capacity over time. He suggests that a cost of time sharing the primary vigilance with other processing activities develops with time on task. The other processing activities can be thought of as attention paid to environmental noise, distracting thoughts and the like.

Recently, another explanation was added. Jansen and Roskam (1989, see chapter 5) connected their inhibition theory to the kind of phenomena discussed in this chapter. In the introductory discussion of the inhibition theory (chapter 1) it was already mentioned that the expected distraction time increases with time on task. This implies that the time devoted to task irrelevant mental activities increases. Since the task relevant processing time is assumed to remain constant, the inhibition theory predicts an increasing RT curve. As will be explained in the subsequent chapters the exact shape of the RT curve follows a decelerating function.

Three theoretical positions will be discussed in more detail. Two of these explanations for performance decrement were already mentioned, namely the loss of attentional capacity explanation of Parasuraman and the inhibition theories of Mackworth, and Jansen and Roskam. We add an explanation which deals with the concept of arousal. Proponents of this last theory are Sanders (1983), Baschera and Grandjean (1979), and Welford (1965).

2.2.1 Loss of attentional capacity

Parasuraman (1984) distinguishes two kinds of vigilance decrement. First, a shift in the decision criterion may be observed, which Parasuraman attributes to a decline in alertness. This decline develops slowly and can be noticed only after more than half an hour of work. The second kind of decrement is a fall in the sensitivity to discriminate targets. This sensitivity decrement emerges soon after the start of the task.

The kind of decrement that will show up, depends on the nature of the task. If the event rate is low and if the task is relatively easily, which is usually the case, then the sensitivity will remain high and a change in the decision criterion will slowly develop. If, however, the task is attention demanding and the event rate is high, then the sensitivity will rapidly decrease (see also Nuechterlein et al., 1983). In Parasuraman's words *'successive-discrimination tasks run at high event rates fall into the category of tasks for which attentional resources must be consistently maintained for efficient performance; although this is possible for short periods of time, it becomes difficult over longer periods, and performance declines due to an effective loss in detectability.'* Parasuraman (1984, p.264).

On several instances Parasuraman (1984, 1985, 1986) employs the processing resources theory (see Wickens, 1984) to explain impairment of performance with time on task. Equating processing resources and attentional capacity, he states that high event rate tasks absorb a large part of the processing resources and that in addition any secondary task that may show up during task execution, will impair task performance. These secondary tasks include environmental noise, distracting thoughts and the like.

The Resource Theory has most extensively been discussed by Wickens (1980, 1984). According to Wickens the terms *capacity, attention, effort,* and *resources* have all been used synonymously to refer to the inferred underlying commodity that enables performance of a task. With reference to task performance, Wickens describes the Resource Theory as follows. Tasks are assumed to demand resources for their performance, and these resources are limited in their availability. Therefore, when the joint resource demand of two tasks exceeds the available supply, time-sharing efficiency drops and will be more likely to do so as the difficulty of either component increases (Wickens, 1984).

Ogden, Levine and Eisner (1979) in their review on the measurement of workload, make a distinction between a dual task paradigm and a secondary task paradigm. In a dual task paradigm attention should be paid equally much to both tasks, whereas in a secondary task paradigm attention should primarily be paid to the first task. This latter paradigm intends to measure the spare capacity left for performing another task, which means that the mental workload of the first task is larger or smaller, according to the extent that it is more or less impaired by adding a second task. It is to this secondary task paradigm that Parasuraman is referring, when he describes the performance decrement in a continuous task as a cost of time-sharing.

2.2.2 Inhibition

The inhibition theory as described by Jansen and Roskam (1989) will be fully discussed in the next chapter. At this place only the connections between this theory and its roots are given some attention. The antecedents of this theory are the reactive inhibition concept of Hull (1943), the mental blocks idea of Bills (1931), and the habituation/inhibition theory of Mackworth (1969).

It should be brought to mind once again that both the refractory period and fatigue are no good as explanations for the (rapid) decline in continuous performance. Stated bluntly, the refractory period is elicited too fast and stays on too short to account for the observed performance decrement, whereas fatigue would turn up much later and cannot dissipate rapidly as is the case if short rest periods are given. Reactive inhibition (to use Hull's term) accumulates during massed trials and dissipates during rest periods. If massed trials are given, long reaction times are expected as a necessary replacement of rest periods.

Mackworth contributed to the development of the inhibition theory by adding a physiological notion to the concept of inhibition and by showing the explanatory value of this concept in a great variety of simple continuous tasks. Although no immediate physiological meaning is intended in the inhibition concept as described in this thesis, the resemblance in observed empirical effects in similar task situations seems at least encouraging for the proposed theory.

2.2.3 Arousal

Following Pribram and McGuiness (1975), Sanders (1983) distinguishes three systems in the control of attention, namely an arousal system as a phasic response to input, an activation system as a tonic readiness to respond and, finally, an effort mechanism as a coordinating and organizing principle. Arousal mainly involves the mesencephalic reticular formation.

In line with Mackworth (1969) and others, Sanders also observes that during the first ten minutes of work, performance decrement is always most noticeable but then an asymptote is reached since there is little change afterwards. According to him, this has been the general finding in studies on vigilance and self-paced serial performance in the laboratory and also in various more realistic tests of long term performance (Sanders, 1983 p.85).

Sanders proposes an explanation in terms of understimulation of the arousal system. Due to too little stimulation, the activity level of the reticular formation drops, and, therefore, the performance will decrease. Baschera and Grandjean (1979) and Welford (1965) gave already the same kind of explanation. They labelled performance decrement on simple, repetitive tasks as monotony, and performance decrement on difficult tasks as fatigue. They conclude from their experiments that repetitive tasks with a low degree of difficulty produce a state of monotony due to the lack of stimulation, whereas a repetitive task with a high degree of difficulty produces a state of fatigue due to a high mental load.

The plausibility of arousal as the responsible system for performance decrement can be strengthened by pointing out that arousal is assumed to affect the encoding stage, that Eysenck's stimulus inhibition explanation deals with encoding and that the sensitivity decrement as described by Parasuraman is best understood in terms of an impairment of encoding (see also Nuechterlein et al.,1983). The encoding stage is the number one candidate for being affected by time on a repetitive task, and arousal, then, is the first energetical system that would be responsible for the observed performance decrement.

2.3 Concluding remarks

In his 1985 article on a multifactorial approach of vigilance performance Parasuraman attacked both the arousal explanation and the habituation/inhibition explanation for a decline in performance with time on a vigilance task. To his opinion, arousal only determines the level of the vigilance, because the overall performance increases from morning till afternoon just as the tonic arousal does. His objections against habituation are more vague. He operationalized habituation as a fall in mean amplitude of the N1 (event related) potential and he indeed observed an overall decrease of the amplitude of N1 over time. Further, he expected and found a steeper decrease of amplitude in the high event-rate task than in the low event-rate task. However, he did not find a larger decrease in amplitude in the active condition than in the passive condition. This last observation made him conclude that habituation is not a good explanation for vigilance decrement.

Parasuraman did, though, observe that in high event-rate conditions (under both active and passive conditions) the mean amplitude of N1 showed a larger decrease than in the low event-rate condition, which is exactly what is predicted by a habituation/inhibition hypothesis. Therefore, our conclusion is that the inhibition explanation is not harmed by the experiment reported by Parasuraman (1985).

The arousal explanation will be disregarded in this thesis because of two reasons. First, both Sanders (1983) and Parasuraman (1984) report that a decline in performance on a simple, repetitive task starts within the first 5 minutes of the task after which a relatively stationary performance is observed. This result was already reported by Bertelson and Joffe (1963). It is, however, generally assumed that arousal changes very slowly (Pribram and McGuiness, 1975; Parasuraman, 1984), which would imply that arousal is not a good candidate for explaining the kind of decrement of present interest.

Another reason for dropping the arousal explanation as formulated by Sanders is that his energetical-stage model is not restrictive enough for the present purposes. For instance, the 'energy' level of the reticular formation can drop because the task is not stimulating enough. However, no intrinsic task characteristics are available to determine, whether a task is stimulating or not. Therefore, this explanation can always be given if performance is observed to decline.

In this thesis we will restrict our attention to two hypotheses that explain performance decrement with time on task, namely the inhibition hypothesis and the loss of attentional capacity hypothesis. In chapter five these two hypotheses will explicitly be contrasted in the homogeneous versus mixed tasks paradigm. In chapter four a massed versus spaced paradigm is employed to show that the experimental tasks used in this thesis yield the same results as found on many occasions in the experimental literature, and, moreover, they yield results that are very accurately predicted by the inhibition theory. This theory is more completely discussed in the next chapter.

3 INHIBITION AND THE MATHEMATICAL MODEL APPROACH

This chapter is devoted to the inhibition theory, of which the processing-distraction models are specific formalizations. Special attention is given to the issue of testing a (inhibition) theory by means of testing predictions derived from some specific formalization (the INHIBITION model). This chapter closes with a description of the experimental paradigm for testing these predictions.

3.1 Introduction

In chapter 2 a great number of experimental studies were briefly reported in each of which a performance decrement with time on task was observed. More precisely, a decelerating performance curve was usually found in well-learned tasks requiring continuous attention in a relatively repetitive situation. It could be stated that repetition of the same mental act leads to inefficient processing. In other words, repetition evokes inhibition.

A very good candidate in explaining this kind of performance decrement is the inhibition theory. In this chapter we will take a closer look at this theory. Special attention is given to the way in which predictions can be derived from this theory by means of a mathematical model. To our opinion the value of a very precise description of the testing procedure is often underestimated. Experimental results can only support a theory to the degree that the predictions are necessary consequences of the theory. The inhibition theory will be tested in this thesis by means of the mathematical model approach. The chain of steps from theory to data are completely described in this chapter. In this way it is possible to evaluate more clearly the experimental evidence given in the following chapters.

3.2 The inhibition theory

To explain performance decrement with time on task we start by assuming that the observed RT on some repetitive RT task is built up of alternating periods of processing and distraction. By distraction time we mean any time not devoted to solving the task at hand. Seen in the light of the performance on the task, distraction time is wasted time. Further, we restrict our following theory only to those RT tasks that contain very little processing time variability. This means that for the subject all the stimuli of the task should be of approximately the same simplicity.

The inhibition theory, essentially, consists of two assumptions:

(1) a RT is composed of alternating periods of processing and distraction,

(2) the inhibition, i.e. the tendency to shift from processing to distraction, increases with the accumulated processing time and decreases with the accumulated distraction time.

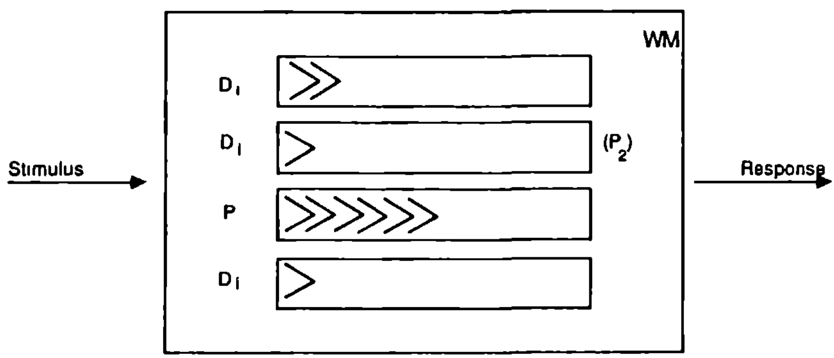


FIGURE 1

A cognitive model of the inhibition theory. The symbol > denotes the activation level of a processor.

The inhibition theory can be illustrated by a cognitive model as presented in figure 1. The task relevant processors are depicted as box P. Constantly activating these processors inhibits them. Putting this another way, the task relevant processors get blocked, and, subsequently, they need a recovery period. Within these recovery periods other mental processes are activated, as indicated by the boxes D_i in figure 1. All these processors are thought to be functionally equivalent to the central processor within the Working Memory concept of Baddeley (1986).

It is an everyday experience that attention cannot be sustained on one issue for a longer period of time, or that concentration fades while reading a book. This inevitable decrease in performance is described by the inhibition mechanism. While executing a simple repetitive task some particular mental processors are time and again activated. However, these processors apparently cannot continuously fulfill the requests. The execution itself deactivates the processor. This is what is meant by the term inhibition.

If the mental processors for the task at hand are inhibited, i.e. if they are inactive, any other task irrelevant mental activity can take place. Time spent on these mental activities is called distraction time. During distraction time the execution of the task is temporarily interrupted.

The inhibition mechanism suggests that the amount of distraction time will be low at the beginning of the task and that it will increase with time on task. Furthermore, the amount of distraction time should be rather small in case rest periods are given frequently, since in that case the mental processors have enough time to recover during unrecorded time. If the mental processors are relatively specific for a certain task it can be predicted that the amount of distraction time is low in case two different tasks are alternatingly administered. All three predictions have repeatedly been supported by experimental data (Van Breukelen et al., 1987b; Jansen & Roskam, 1989).

3.3 Modeling the inhibition theory

From the (general) inhibition theory only general predictions can be derived. According to the theory, the more work per trial, and the less time between trials, the greater should be the tendency to shift from processing to distraction. A first prediction, which follows immediately from this formulation of the theory, is that the RT curve over a massed series of trials will increase. In addition, it is predicted that the RT curve will be stationary, if the subject is given rest between trials.

However, in case more specific predictions are desired, the theory should be formulated in terms of precise mathematical assumptions. In the next sections some mathematical formalizations of the processing-distraction theories will be presented. Most important is the INHIBITION model which is a mathematical formalization of the inhibition theory. It should be stressed that the proposed models have the advantage of their precision, but at the same time the disadvantage that some technical assumptions have to be made, and some restrictive conditions have to be imposed, which are not strictly necessary for the theory. For instance, very specific predictions can be derived from the INHIBITION model, but the assumption that the processing time per trial will be constant will never be completely fulfilled.

More generally speaking, the mathematical model approach has the following structure (see figure 2). Starting from the inhibition theory a specific formalization is given. In this case the INHIBITION model serves as the formalization, from which relatively precise predictions can be derived, e.g. a negatively exponential increasing RT curve is expected and it is also expected that the RT variance will increase. These predictions can straightforwardly be tested on experimental data. It is important to note, that the connection between theory and data is very clear in case of this mathematical model approach. Without a specific formalization of a theory it often happens that the experimental data neither support nor harm the theory.

The development of the inhibition theory moved along the lines of the mathematical model approach. It started by a very simple model, the Gamma model, and gradually became more complex and more in line with the empirical facts. In the next sections we will discuss the Gamma model, the Poisson-Erlang model and the INHIBITION model.

3.4 The processing-distraction theory and models

The theoretical considerations of the processing-distraction theory are that the solution of a problem requires the execution of a series of subprocesses, and that within a subject the execution time for these subprocesses will always be the same provided that learning effects, and shifts of the speed-accuracy tradeoff are absent. It was assumed, further, that the subject having executed a subprocess does not necessarily continue immediately with the execution of the next subprocess, but may enter in a state of non processing, called distraction.

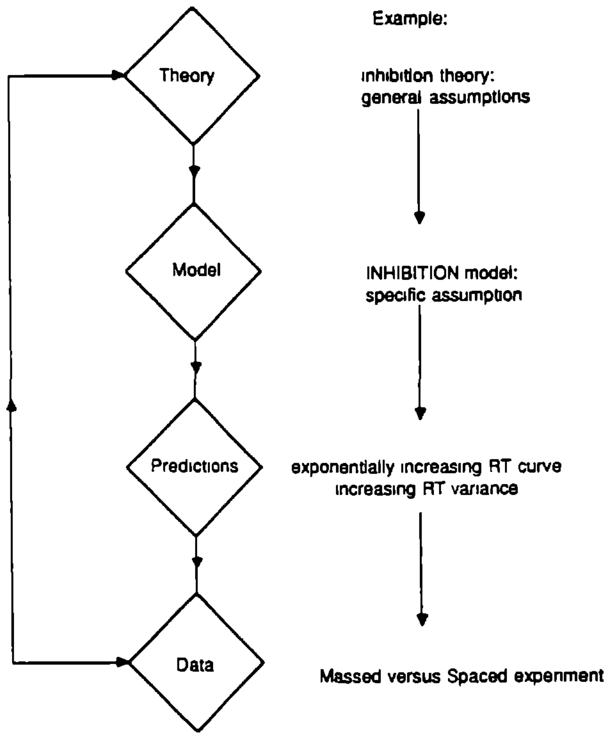


FIGURE 2

An illustration of the mathematical model approach

In other words, the response times consist of processing time and distraction time. The total processing time per task unit is assumed to be constant. Finally, it is assumed that a distraction can only occur after the execution of a subprocess, which implies that the number of distraction periods per RT is restricted by the number of subprocesses necessary for the solution of a problem.

For the early processing-distraction theory there existed only a minimal distinction between theory and models. For instance, both the theory and the model adopt the assumption that the processing time should be constant per task unit. The inhibition theory as presented in this thesis is more general, but the mathematical model incorporates specific assumptions concerning the alternation of processing and distraction. The inhibition theory is not restricted by a constant processing time assumption nor by a specific description of alternation of processing and distraction periods, whereas the INHIBITION model is built upon the constancy of processing time assumption and upon the assumption that the transition rate of shifting from processing to distraction is described in a very specific way (see paragraph 3.5).

The models constructed for the (early) processing-distraction theory and for the inhibition theory do share some basic assumptions. These assumptions will be highlighted in the following sections.

3.4.1 Introduction to the experimental paradigm

For easy understanding of the following sections, we first introduce the general characteristics of the experimental paradigm which we use. It will be described in detail in the last part of this chapter and in later chapters. Essentially, we use a series of trials of simple tasks, like the addition of two digits, and a YES/NO response format, e.g. 3 + 5= 9 YES/NO. The subject is instructed to respond fast and accurately. RT is recorded for each item from stimulus onset till the pressing of the response key.

For proper experimentation, all items have to be of the same difficulty, and be equivalent in terms of the mental process involved in responding to it. Further, the series of trials has to be carefully balanced with respect to the sequence of YES/NO responses, with respect to repetitions of items, and with respect to all other factors which might systematically affect the response time.

For the analysis, short balanced sequences of typically 6 trials are blocked and treated as the unit of the analyses. These trial blocks better fulfill the requirement of having a constant processing time than the single trial does. (This constancy of processing time assumptions will be discussed below.) Using trial blocks as the unit of the analyses yields a sequence of, say, 40 consecutive RTs (on 40*6=240 trials), of which the statistical properties are to be analyzed and confronted with the predictions of the model. Moreover, the RTs will presented in seconds in stead of in milliseconds, since the sum of six trial RTs usually varies between 2.5 and 5.5 seconds depending on the kind of task that is administered.

The experimental variation within the experimental paradigm chosen in this thesis, consists of, e.g. rest periods between blocks of trials, or alternating different kinds of tasks (such as additions alternated with letter matching).

3.4.2 Some basic assumptions

The main assumption of all the processing-distraction models is that a response time (RT) is the sum of alternating processing and distraction periods. In addition, all the models mentioned in this chapter assume that the total processing time per RT is constant for a given subject, task, and condition. This additional assumption puts some heavy constraints on the task and its administration. The task should be overlearned, and its stimuli should be of the same simplicity. Besides the required absence of learning effects, the subjects should work at the same speed-accuracy trade-off throughout the task. Since errors may have a disruptive effect on the processing time, the subjects will be required to work (almost) errorless. In this way the speed-accuracy trade-off is also set at a fixed rate.

Assuming that the processing time per RT is constant (indicated by parameter A), all RT variability is due to distraction time variability. The distraction time per RT depends upon the number of the distraction periods and each of their durations. The third assumption which is adopted by all of the processing-distraction models is that the duration of the distraction periods is exponentially distributed with parameter δ. So, the models that will be described in the sequel differ on the assumption regarding the number of distraction periods. For instance, the model which assumes (in addition to the above mentioned assumptions) that the number of distractions is constant per RT, predicts a gamma distribution for its RTs. Such a distribution is single peaked and skewed to the right, as are most of the empirical RT distributions. This specific model is called the Gamma model. The other models to be treated in this chapter are the Poisson-Erlang model (PE-model), the INHIBITION model and the IMAX model.

Summing up, the following three assumptions are adopted by all processing-distraction models mentioned in this thesis:

(1) RT is the sum of alternating periods of processing and distraction.

(2) The total processing time per RT has a certain, constant value A for a given subject, task, condition, and level of accuracy.

(3) The duration of the distraction periods is exponentially distributed with parameter δ.

The following models merely differ on the assumption concerning the number of distractions per RT.

3.4.3 The Gamma model

The most simple model of these processing-distraction models is the Gamma model. It assumes that the number of distractions per RT, denoted by parameter n, is constant. From a theoretical point of view it was expected that after each subprocess a distraction, however short, would occur. So, according to this model the fluctuations in the RTs are reflected in the distribution of the duration of the sum of a constant number of distraction periods. Let A denote the constant actual processing time per trial, n denote the number of distractions per trial and δ the rate parameter of the exponential distribution for the distraction times, then the distribution of the total response time, RT, is defined as

$$F_{RT}(t) = \int_0^t \delta^n / (\Gamma(n)\,(x-A)^{n-1} e^{-\delta(x-A)})\ dx \qquad \delta, n>0. \qquad [3]$$

The expectation and the variance of RT can be written as

$$E(RT) = A + (n/\delta)$$

$$Var(RT) = n/\delta^2 \qquad [4]$$

As was mentioned, the gamma distribution is unimodal and positively skewed. Most observed RT distributions have the same shape.

3.4.4 The Poisson-Erlang model

The Gamma model seemed too unrealistic by expecting a distraction after each subprocess. It, then, would be theoretically more plausible to relate the number of distractions to some particular stochastic process, in which case a distraction has a certain probability to occur after the end of a subprocess (Roskam (personal communication, 1977) was the first to propose this). The Poisson process seemed to be the most promising mechanism for determining the number of distractions per RT. Starting from these propositions Pieters (1981; Pieters and Van der Ven, 1982) developed the Poisson-Erlang (PE) model.

This model assumes that the number of distractions per trial is Poisson distributed with parameter γ. Formally, the PE model is a compound Gamma model. It arises if we assume that the Gamma parameter which stands for the number of exponential variables, is itself a random variable. In case of the PE model we assume that this parameter has a Poisson distribution.

The distribution of RT is determined by the distribution of the total distraction time per RT. This distribution function is derived using the following assumptions:

(1) Each distraction period D_i, i=1,2,...,m has an exponential distribution with parameter δ, defined by

$$f_{D_i}(t) = \delta e^{-\delta} \qquad [5]$$

(2) The number of distraction periods, M, has a Poisson distribution with parameter γ:

$$P(M=m) = \gamma^m e^{-\gamma}/m! \qquad m=0,1,2,.... \qquad [6]$$

Since γ indicates the rate of distractions per processing time, γ can also be written as λA.

Using standard results from probability theory, Pieters (1981, 1984) showed that the distribution of the total distraction time per RT, D, is a compound Gamma distribution, called the Poisson-Erlang distribution, which is defined by

$$F_D(t) = 1 - e^{-(\gamma+\delta t)} \sum_{m=0}^{\infty} \gamma^{m+1}/(m+1)! \sum_{j=0}^{m} (\delta t)^j/j! \qquad t>0 \qquad [7]$$

Noting that the processing time per trial, A, is assumed to be fixed, the distribution of RT is obtained by using the transformation:

$$RT = D + A \qquad [8]$$

The distribution of RT, therefore, is given by

$$F_{RT}(t) = 1 - e^{-(\gamma+\delta(t-A))} \sum_{m=0}^{\infty} \gamma^{m+1}/(m+1)! \sum_{j=0}^{m} (\delta(t-A))^j/j!$$

$$\text{where } t \geq A \qquad [9]$$

This description of the distribution of RT leads to the following expectation and variance of RT:

$$E(RT) = A + (\gamma/\delta)$$

$$Var(RT) = 2\gamma/\delta^2 \qquad [10]$$

The PE distribution is also unimodal and positively skewed like the Gamma distribution. Comparing equations [10] and [4] it becomes evident that the PE model predicts a larger variance. Considering the shape of the RT distribution, this means that the PE model predicts a thicker tail towards the right end of the distribution.

3.4.5 Experimental tests of the PE and the Gamma model

Pieters (1984, 1985) reported two experimental tests of the Gamma model and the PE model. In the first experiment the stimuli consisted of 105 addition problems. The subject was instructed to add two numbers each consisting of two digits, multiply the digits in the sum and report whether the extreme left digit in the result was odd or even. A within subjects design was used with 40 subjects and 8 conditions. The conditions consisted of the complete crossing of three two-level factors: (1) item difficulty, (2) accuracy-bonus, and (3) speed pay-off. Each condition was preceded by (at least) 10 practice trials.

In the analysis the Decision model of Hohle (1967) was also considered. Since the distribution of the Kolmogorov-Smirnov goodness-of-fit statistic could not be derived for this particular case, Pieters used the absolute value of this statistic merely as a descriptive measure in the evaluation of the fit of the three models. Overall, the Gamma model gave the worst fit, and the PE model the best fit. Further, rank orderings of these statistics were computed for each subject and condition separately, leading to 320 measures of fit. In 291 cases the fit of the PE model was the best, followed by the fit of the Decision model. In 29 cases the fit of the Decision model was better than the fit of the PE model. In all cases the fit of the Gamma model was worse than the fit of the other models.

Regarding the effects of the experimental factors the PE model predicts that the processing time, A, increases with item difficulty and accuracy. Since $\gamma = \lambda A$ it was also expected that γ would increase. The speed pay-off factor, on the other hand, should have an effect on the distraction parameters and no effect on the processing time. These three predictions were only partially supported, because no effect on parameter γ could be reported.

The conclusions from a second experiment on mental rotation were the same as for the first experiment on mental addition: the experimental data suggested a bad fit of the Gamma model and a good fit of the PE model. Furthermore, the experimental effects on estimated parameter values appeared to confirm the predictions of the PE model.

However, for estimating the model parameters and for determining the goodness-of-fit of the PE model, trend in RT over trials had to be eliminated from the data. It is immediately evident from equation [10] that the PE model predicts a stationary RT series. In most applications, however, the individual RT series exhibit some form of a trend, which is often increasing (given that the subjects have had enough practice). The major criticism on the PE model, now, is that the trend in the RTs cannot be eliminated without affecting the estimation of the distraction parameters (see Van Breukelen, Van der Ven & Van den Wollenberg, 1987c, for a detailed discussion of this issue). The PE-model only applies in those series that are stationary from the start.

3.5 The INHIBITION model

The logical successor of the PE-model, therefore, is a model in which trend in the RTs is predicted. Such a model, called the INHIBITION model, was developed by Van der Ven, Smit and Jansen (1989). The number of distractions in this model depends on the preceding amounts of processing time and distraction time. Specifically, the transition rate of shifting from processing to distraction is assumed to increase linearly with the accumulated processing time, and to decrease linearly with the accumulated distraction time, and has a certain level at the beginning of the task. The crucial assumption, then, is

$$I(t) = \max[0\ ,\ I_0+\mu_1 P(t)-\mu_2 D(t)] \qquad \mu_1,\mu_2>0$$

where I_0 = the initial value of the transition rate,
$P(t)$ = the accumulated amount of processing time, and
$D(t)$ = the accumulated amount of distraction time [11]

The transition rate is the hazard rate of a period of processing, i.e. the probability that at time t, a distraction period starts given that processing is going on at time t. Whereas the number of distractions per RT is independently and identically distributed in the PE-model, the number of distractions within the INHIBITION model depends on the transition rate $I(t)$. This rate $I(t)$ could be called inhibition. If the inhibition increases, a distraction period will become more likely.

At least two empirical consequences follow from this description of the INHIBITION model (details can be found in Van Breukelen et al., 1987b, and Van der Ven et al., 1989): (1) a negative autocorrelation is predicted in a continuous RT series. In a short RT little distraction has occurred, which means that at the next trial the inhibition is relatively high. As a consequence the probability of a distraction is relatively high, which makes it more likely that the duration of the next RT will be relatively long. And (2) if the initial inhibition I_0 is below its stationary expectation (which equals $\mu_1\delta/\mu_2$), then the distraction time will be low at the beginning of the task and, consequently, $E(RT_k)$ and $Var(RT_k)$ will show an increasing trend, and they will become stationary in the long run. The initial inhibition could also be above its stationary expectation, but as will be explained in the next section, that would not be very plausible from a psychological point of view.

The mathematics of the INHIBITION model are quite tedious. Given the non-stationary character of the predicted RTs, it is not possible to derive an overall RT distribution. Moreover, since the hazard rate function fluctuates continuously, it is also not possible to derive a theoretical distribution for the RT on trial k. Van der Ven, Smit and Jansen (1989) gave a thorough mathematical description of the INHIBITION model, the moments of its process and the moments of the RTs. The mathematical results of Van der Ven et al. (1989) which are more complete than those of Van Breukelen et al.(1987b), will be rewritten in a different parameterization. Given the presently used description of the PE model and of the IMAX model, it seems more consistent to use the parameterization of the INHIBITION model given by Van Breukelen et al.(1987b). Appendix A shows the correspondence between the two parameterizations.

In the general case the expectation of RT on trial k is written as

$$E(RT_k) = A + \mu A + ((I_0 - \delta\mu)/\mu_2)(1-r)r^{k-1}$$
$$\text{with } \mu_1, \mu_2, \delta, A > 0,$$
$$\text{and } \mu = \mu_1/\mu_2$$
$$\text{and } r = e^{(-A\mu_2/\delta)},$$
$$\text{where } k = \text{trial number} \qquad [12]$$

Consequently, the model predicts an exponential trend in the sequence of RT_k, $k=1,2,\ldots,n$. This trend may decrease, if $I_0 > \mu\delta$, or increase, if $I_0 < \mu\delta$, since all model parameters except I_0 are by definition greater than zero.

The variance of RT in the general case was also derived by Van der Ven et al. (1989). Omitting terms with r^{2k}, which tend to move toward 0 more rapidly, we can write

$$Var(RT_k) = 2(\mu/\mu_2)(1-r) + (2/\delta)((I_0 - \delta\mu)/\mu_2)(1-r)r^{k-1}$$
$$\text{again with } \mu = \mu_1/\mu_2$$
$$\text{and } r = e^{(-A\mu_2/\delta)}. \qquad [13]$$

Therefore, $Var(RT_k)$ will show a trend with the same direction as $E(RT_k)$, because also in this case $(I_0 - \delta\mu)$ determines whether the variance will increase or decrease. It should be noticed that both in equation [12] and in equation [13] the righthand term containing r^{k-1} will approach zero for large k.

In the stationary case, i.e. if $I_0 = \delta\mu$, the equations for the expectation and the variance of the RT become

$$E(RT) = A + \mu A$$
$$Var(RT) = 2(1-e^{-A\mu_2/\delta})(\mu/\mu_2)$$
$$\text{with } \mu = \mu_1/\mu_2 \qquad [14]$$

For estimating the model parameters we make use of the exponential trend of $E(RT_k)$. Specifically, the expected RT is an exponential function of the trial number:

$$E(RT_k) = \alpha + \beta\theta^{k-1} \quad \text{with } 0 < \theta < 1$$
$$\text{where} \quad k = \text{trial number} \qquad [15]$$

The stationary expected value of RT is α, which is reached for large k. Parameter θ of equation [12] determines how fast α is reached. If θ is near zero, stationarity is attained after a few trials, but if θ is near one, the trend becomes almost linear. Parameter β determines the slope of the trend curve. A positive β yields a decreasing RT curve, whereas a negative β gives an increasing curve.

The parameters α, β, and θ of equation [15] can be written in terms of the model parameters of equation [12]:

$$\alpha = A(1+\mu)$$
$$\beta = (1-\theta)(I_0-\delta\mu)/\mu_2$$
$$\text{and} \quad \theta = e^{(-A\mu_2/\delta)} \qquad [16]$$

Substituting the equations for α, β, and θ of [16] into equation [15] yields again equation [12].

The model parameters A, I_0, μ_1, μ_2, and δ can be estimated by means of the equations given in [16] together with the stationary variance, which was given in equation [14]. To estimate these model parameters it is also necessary to fix A. For the INHIBITION model A is estimated by the minimum RT, which is a biased but acceptable and only available estimator at hand (see Van Breukelen, 1989b).[4] The other model parameters can be estimated by means of the following equations

$$\delta = \frac{2(1-\theta)(\alpha-A)}{(-ln\theta)\sigma^2} \qquad [17]$$

$$\mu_1 = \frac{2(1-\theta)(\alpha-A)^2}{A^2\sigma^2} \qquad [18]$$

[4] To be complete, there exists an additional equation for estimating the model parameters, i.e. the equation for the first lag autocorrelation (see Van Breukelen, 1989b):
$\rho_1 = (1-\theta)/2$. However, the observed autocorrelation is highly unreliable, and, moreover, the autocorrelation showed to be empirically inseparable from the trend in the data.

$$\mu_2 = \frac{2(1-\theta)(\alpha-A)}{A\sigma^2} \qquad [19]$$

$$I_0 = \frac{\beta(\alpha-A)}{A\sigma^2} + \frac{2(1-\theta)(\alpha-A)^2}{(-\ln\theta)A\sigma^2} \qquad [20]$$

The INHIBITION model is theoretically the model which is by far to be preferred to the other available models. However, this model has two major drawbacks: (1) the model has too many parameters to estimate them reliably from the data. In addition, the exponential function given in equation [15] can sometimes (i.e. in approximately 25% of the cases) not be fitted due to values of θ which are either too close to zero or too close to one. (2) the model predicts a negative autocorrelation, which was not reliably found in the empirical data in the applications of the model until now.

3.6 Testing the inhibition theory

It was already mentioned that from (the general description of) the inhibition theory only a few global predictions could be derived. Increasing RT curves are predicted for massed series of trials, whereas stationary RT curves are predicted for spaced series. Furthermore, RT in (massed) series of alternating tasks should increase less than in (massed) series of a single task. In this paragraph we will sum up all the available predictions for testing the inhibition theory.

3.6.1 The predictions

Formalizing the inhibition theory in terms of the INHIBITION model yields specific predictions. In a massed series of trials the INHIBITION model predicts: (1) an increasing RT curve, and (2) an increase in the (residual) RT variance, as was given in the equations [12] and [13]. This model also predicts a negative first lag autocorrelation, but given the disappointing results on the autocorrelation thus far this prediction will only be treated as a side-issue.

In case rest periods are given between trials as is done in a spaced condition, the inhibition will dissipate during rest and distraction time will, therefore, be less than in a massed condition. The specific predictions for massed versus spaced, then, are:

(3) distraction time is larger in a massed condition than in a spaced condition,
(4) the RT curve in a spaced condition will be less increasing than in a massed condition,
(5) the RT variance in a spaced condition will be less increasing than in a massed condition.

In terms of gross RT measures these predictions imply that (given that the processing time is the same in both massed and spaced conditions)

(6) the mean RT (RT_{Mean}) is larger in the massed condition than in the spaced condition,
(7) the variance of RT ($RT_{Variance}$) is larger in the massed than in the spaced condition.

3.6.2 Estimation problems

Prediction (1) through (5) are stated in terms of model parameters. This implies that the parameters of the INHIBITION model have to be estimated from the observed data. There exist, however, two major estimation problems with respect to the INHIBITION model: (1) the model has too many parameters to estimate them nicely from the data, and (2) even if the processing time parameter A is fixed, the model parameters still can not be estimated in 25% of the cases due to the problem that the predicted exponential RT curve cannot be fitted to the data since θ is either too close to zero or too close to one. It seems that the INHIBITION model is too difficult for practical purposes.

The solution proposed here to solve this problem is to approximate the INHIBITION model by a model with less parameters. The IMAX model will serve this purpose. This model is described in detail in a following paragraph. The predicted RT curve of the IMAX model is empirically hardly distinguishable from the predicted RT curve of the INHIBITION model (see Van Breukelen, 1989a, 1989b). The IMAX model also predicts an increase in the RT variance as will be shown in [22].

In chapter 1 it was mentioned that a model could be tested by a goodness-of-fit test or a test on the model parameters under different experimental conditions. Neither of these two kinds of tests will be presented in this thesis. The main reason is that we do not intend to test the *model*, but we want to test the *theory*. Several other reasons for not testing the model by its parameters are given in the next paragraph dealing with the IMAX model.

Instead of the model parameters we will use some robust estimators for the main components of the IMAX model, which are the processing time and the distraction time. The processing time per RT is estimated by the minimum RT ($RT_{Minimum}$) and the distraction time, then, is estimated by the difference between RT_{Mean} and $RT_{Minimum}$.

The increase of the RTs is determined by fitting the observed RT curve to the trend curve predicted by the IMAX model (see below equations 21-26). The increase in the variance of the RTs is tested as follows. A residual time series is calculated by subtracting the fitted IMAX model trend function from the observed time series. This residual time series, then, is partitioned into 5 consecutive subseries of 8 RTs each. The mean, variance and error rate are calculated for each of these subseries. A test on trend in the variances of the 5 subseries is, then, used as the test of an increase in the variances of the RTs.

3.6.3 A modified mathematical model approach

Due to the just mentioned estimation problems, the model approach as depicted in figure 2 must be modified slightly. The test of the inhibition theory is, now, obtained by the chain of steps given in figure 3.

Figure 3 shows that getting from the INHIBITION model down to the data demands a lot of additional assumptions. This figure is very explicit with respect to the assumptions adopted, which means that the value of the conclusions drawn from the experimental results reported in this thesis can be judged against this picture. Comparing figure 2 and figure 3 it turns out that the mathematical model approach in this thesis is modified with respect to the derivation of the predictions from the model. In this case an additional step became necessary because the parameters of the INHIBITION model could not be easily estimated. The supporting evidence of the empirical data for the theory now also depend on the biasedness and unreliability of the estimators added in step 3 (see figure 3).

For instance, assuming that $RT_{Minimum}$ is a good estimator of the processing time, the amount of distraction time can be easily compared between different experimental conditions, since the distraction time, then, is given by (RT_{Mean}-$RT_{Minimum}$). In other words, the supporting evidence of the experimental results reported in this thesis depends upon the applicability of the assumptions shown in figure 3.

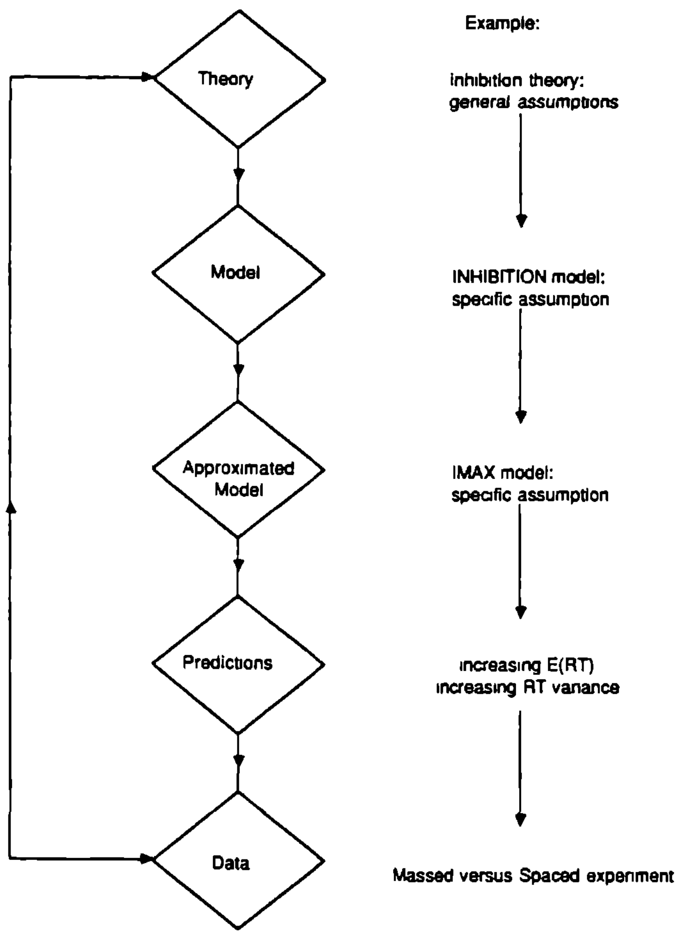


FIGURE 3
The steps of the modified mathematical model approach

The predictions given in section 3.6.1 should be enhanced with respect to the fact that the data are fitted to the RT curves predicted by the IMAX model and the fact that the processing time will be estimated by $RT_{Minimum}$. The IMAX model is treated in the next section. Estimating the processing time by $RT_{Minimum}$ will be discussed on several instances in the next chapters of this thesis.

3.6.4 The IMAX model

To overcome the estimation problems of the INHIBITION model a simplified model has been constructed by Jansen and has been worked out by Van Breukelen (Van Breukelen, 1989a, 1989b). This model is called the IMAX model. The transition rate of shifting from processing to distraction depends in this model only upon the accumulated processing time.[5] To be specific:

$$I(t) = \min\,[v \times P(t),\ I_{max}],$$

where $P(t)$ is the accumulated processing time, and I_{max} is the maximum value of $I(t)$. [21]

The inhibition theory assumes that distractions serve the purpose of reducing inhibition or mental fatigue. This implies that the theory predicts an increasing RT curve and also that the inhibition dissipates with distractions or rest, i.e. with time not devoted to the task at hand. The IMAX model lacks an inhibition mechanism, since there is no recovery from mental fatigue during distractions. Therefore, the IMAX model is not an 'inhibition model'.

[5] Psychologicaly it seems not plausible to get decreasing RT curves if a subject starts afresh and if also the requirement of overlearnedness of the task is fulfilled. However, mathematically an extension of equation [21] to the case of decreasing curves could be given by letting v take on negative values and by setting a lower limit in terms of $-I_{max}$. This extension will not be pursued in this thesis, since decreasing curves are not thought to be due to the same mechanism as are increasing curves. Increasing curves are assumed to be the result of the inhibition mechanism, whereas decreasing curves are regarded as the result of an ongoing learning process. In a more sophisticated formulation, the inhibition mechanism is stronger than the learning process for increasing curves, whereas the learning effect covers up the inhibition effect for the decreasing curves. If mainly decreasing curves are observed (even after enough practice), then the inhibition effect is not interesting, even if something like inhibition exists.

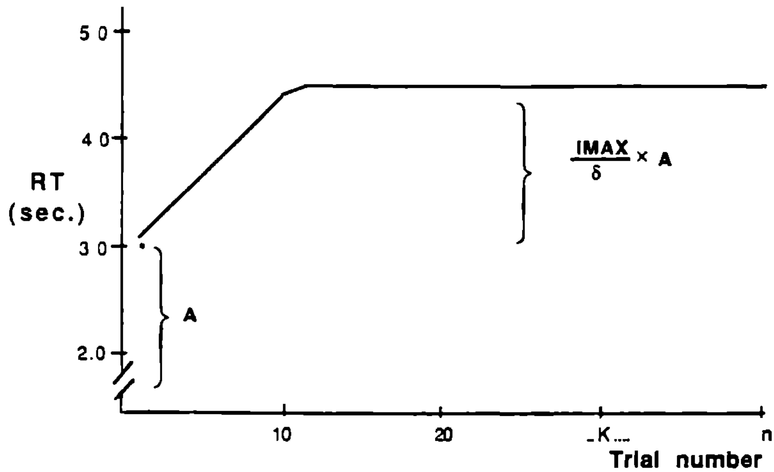


FIGURE 4

The predicted RT curve of the IMAX model

(for explanation see text)

However, the IMAX model is useful as a mathematical approximation of the INHIBITION model. The IMAX model predicts both an increasing RT curve and an increasing variance (see equation [22] and figure 4). This predicted RT curve is empirically almost not distinguishable from the RT curve predicted by the INHIBITION model (see Van Breukelen, 1989a). The parameters of the IMAX model can be easily estimated for all observed RT curves without putting constraints on any of the parameters. A great disadvantage of the INHIBITION model is the fact in about 25% of the observed RT curves the trend function of equation [15] can not be fitted due to an extreme value for θ. The main reason to apply the IMAX model, therefore, is that *all the observed RT curves can be fitted.* So, by using the IMAX model we get a better idea of the number of increasing and decreasing curves and of the shape of the increasing curves (slowly or fastly increasing, a large or a small increase). The estimation procedure of the IMAX model parameters is given in the sequel.

The description of the transition rate of equation [21] leads to the following expectation and variance of the RTs:

$$E(RT_k) = A + (k-0.5)\nu A^2/\delta \quad and$$

$$Var(RT_k) = (2k-1)\nu A^2/(\delta^2)$$

$$\text{with } k \leq \theta, \text{ and}$$
$$\theta \text{ is the trialnumber where } I(t) \text{ reaches } I_{max}. \qquad [22]$$

If the maximum value of the inhibition is reached, the equations for the expected RT and the RT variance are the same as those for the PE-model in which γ is then equal to AI_{MAX}. To be specific:

$$E(RT_k) = A + AI_{max}/\delta \text{ and}$$

$$Var(RT_k) = 2AI_{max}/\delta^2$$

$$\text{where } k > \theta \qquad [23]$$

The implications of the IMAX model are no autocorrelation, an increasing trend in the expected RT, and an increasing trend in the RT variance. These last two predictions are given in equation [22]. Figure 4 illustrates the increase in the RTs. The parameters were given the following values: $A=3.0$, $\delta=8$, $I_{max}=4$, and $\nu=0.133$.

The parameters of the IMAX model are estimated as follows. First, the trend function of equation [24] which equals the trend predicted by the IMAX model, is fitted to the data using a conditional least square method (see Appendix B).

$$E(RT_k) = \alpha + \beta(k-0.5), \quad \text{for all } k \leq \theta$$
$$E(RT_k) = \alpha + \beta\theta \qquad \text{else}$$

$$\text{where } k \text{ is the rank number of a trial} \qquad [24]$$

Again we can recalculate equations [22] and [23] from equation [24]. In this case the parameters of the trend function can be written as

$$\alpha = A$$

$$\beta = \nu A^2/\delta$$

$$\theta = I_{max}/\nu A \qquad [25]$$

Secondly, the equations of α, β, and θ given in [25] together with the variance of the stationary part of this time series given in [23] are required to calculate the model parameters. The specific equations are:

$$A = \alpha$$

$$\delta = \frac{2\beta\theta}{\sigma^2}$$

$$I_{MAX} = \frac{\delta\beta\theta}{A}$$

$$\nu = \frac{I_{max}}{\theta A} \qquad [26]$$

An obvious advantage of the IMAX model over the INHIBITION model is that all the model parameters can be estimated from the data without any constraints.

The IMAX model and the inhibition theory. Since our main goal is to test the inhibition theory, as well as a number of hypotheses - to be presented later - related to it, we will be mainly concerned with experimental effects on mean, variance, and trend in RT, and with the decomposition of RT into processing and distraction time. We consider the INHIBITION model as the most appropriate formalization of the theory, and therefore, our predictions will be derived from the INHIBITION model. However, in analyzing the data, we want to free ourselves from the practical limitations of the INHIBITION model, and, therefore, use the IMAX model as a feasible approximation to the INHIBITION model. Thus, for example, we will use the IMAX model to fit trend curves to series of RTs. Details will become clear in the following sections.

3.6.5 No tests on model parameters

Throughout his thesis no goodness-of-fit test, nor any ANOVA on model parameters were performed. Instead of that, global measures as the number of increasing and decreasing individual RT curves were reported, and ANOVA's were done on the task variables, which were treated as robust (but biased) estimators of the model parameters.

There are at least two good reasons for reporting the experiments in the way that it was done: (1) the inadequacy of the IMAX model for spaced conditions, or for mixed tasks conditions, and (2) the lack of a goodness-of-fit statistic.

First, model parameters can not be justifiably estimated from RT curves obtained from either the spaced condition or the mixed condition. For the spaced condition the IMAX model or the INHIBITION model take no account of the fact that the inhibition should decrease during a rest period. Similarly, these models do not include the recovery periods provided by the processing of a second task in case of the mixed condition. Therefore, no ANOVAs can be done on model parameters for differences between conditions, whenever spaced or mixed conditions are involved.

Secondly, a goodness-of-fit test on the observed RT distribution of data obtained in a massed condition is very difficult, since goodness-of-fit statistics lack for these kind of data. First of all, the RT distributions of the IMAX model and of the INHIBITION model are unknown. However, it is known that the stationary part of the RT curve predicted by the IMAX model is Poisson-Erlang distributed. Van Breukelen (1989a) calculated a measure closely related to the Kolmogorov-Smirnov statistic for these stationary segments of the IMAX RT curves. He obtained values for this goodness-of-fit measure which appeared to indicate a good fit of the IMAX model for his data.

Finally, the main distinction made in the IMAX model or the INHIBITION model is that between processing time and distraction time. For the moment it seems wise to restrict the interpretation of model parameters to this main distinction. The robust estimators of these parameters are $RT_{Minimum}$ and $(RT_{Mean}-RT_{Minimum})$ respectively.

3.7 The experimental paradigm

3.7.1 Introduction

Two reasons can be mentioned in favor of devoting a separate section to the data structure and analysis of serial RT data. First, the RT analysis can be done on the level of the subject, and on the level of conditions or groups of subjects. Most of the times it is left to the reader to notice on which level the analyses are performed. Since this kind of paradigm is still not familiar among experimental psychologists an outline will be helpful.

Secondly, the data structures and analyses are very similar for all of the experiments reported in this thesis. However, only a few analyses are reported on every occasion, and several specific analyses are added depending on the specific hypotheses tested. This implies that the knowledge of the variables available might give a lead to further exploratory analyses.

3.7.2 Task requirements

The constancy of processing time is one of the assumption of the INHIBITION model (as well as the IMAX model). This assumption puts some severe restrictions on the construction of the task. RT fluctuations due to stimulus repetitions or response repetitions should be banned as much as possible. Especially for this latter source of noise in the data, but also for sources like stimulus difficulty and so on, the unit of analysis is not the RT of a trial, but the RT of a block of trials. A block mostly consisted of six trials. This means that the RT of six consecutive trials was taken as the unit of RT analysis. Within each block of trials the response sequence was controlled. Also the effect of the other sources of RT fluctuation was minimized by the application of the block as unit of the analysis. Finally, the task itself should not contain some kind of random search process which would make the processing time vary.

Administering long practice series also served the purpose of making the constancy of processing time assumption plausible. Inspecting the empirical RT curves should give an indication whether a learning effect is predominantly present or not. Additional information was gathered from the changes in the error rate over time. Ideally, no changes in the error rate are expected.

3.7.3 Data structure

In all of the experiments to be reported subjects received two-choice RT tasks. Sitting in front of a computer screen they had to press one of two buttons in response to the presentation of a stimulus. The response stimulus interval (RSI) was 5 milliseconds, which is just enough to notice that a new stimulus is presented. The number of trials in a series was 240 for the experimental conditions and 120 for the practice conditions. These numbers apply for most of the experiments.

Each key press elicited the registration of the following data: trial number, stimulus number, the RT, and the identification of the button that was pressed. These are the raw data in all of our experiments.

These raw data were first of all screened for outliers, which are in our experiments RTs below three or above four standard deviations from the mean of the RT series. In the first experiment (see chapter 4) the outliers were replaced by the mean of the RT series. In the other experiments only RTs above a fixed criterion were replaced by the RT_{Mean} of a subject's own RT series. This last criterion was the same for all subjects on a specific task. For instance, a level of 4 seconds *per trial* was the limit for adults working on a Bourdon task. We assume that RTs above this criterion are due to extra-experimental effects, such as visual disturbance caused by the computer screen. These very high RTs occurred once or twice per condition, which equals once or twice on every 10 time series, which equals once or twice per 2400 trials.

As was already mentioned in section 3.4.1, the analyses were done on the RTs per block of (six) trials. So, whereas the RT per trial was about 500 to 800 milliseconds on the average, the RT per block was about 3 to 5 seconds on the average depending on the kind of task. All variables mentioned in the next section are based on these block RTs.

3.7.4 Variables

For a number of reasons the set of variables shown in table 1 were derived from the RT data. It is stressed that the RT per block of trials served as the unit for gathering these variables. First of all, each RT series is classified by its subject number and condition number. The usual RT variables to be calculated are RT_{Mean}, $RT_{Variance}$, and $RT_{Skewness}$ along with $RT_{Minimum}$ and the error rate.

TABLE 1

The dependent variables

RT variables
RT_{Mean}, $RT_{Variance}$, $RT_{Skewness}$,
$RT_{Minimum}$, Error rate,
α, β, θ of trend function [24],
Stationary $RT_{Variance}$,
Slope of linear trend function,
SSmean, SS-imax-trend, SS-linear-trend,
F_1, F_2, F_3 of equation [27]
Model Parameters
A, the processing time,
I_{MAX}, δ, ν
Residual time series
Section means
Section variances

Secondly, the trend parameters of equation [24] are estimated using a conditional least square method (see Appendix B). The trend parameters α, β, and θ together with the stationary variance are required to calculate the model parameters.

Thirdly, to evaluate the parsimony of the fitted IMAX model the error sums of squares of the mean, of a linear function, and of the trend function of equation [24] are calculated. For the same purpose the following F-statistics are derived:

$$F_1(2,37) = \frac{(SSmean - SSexp)}{2MSmean}$$

$$F_2(1,37) = \frac{(SSmean - SSlin)}{MSmean}$$

$$F_3(1,37) = \frac{(SSlin - SSexp)}{MSmean}$$

where SSmean is the SS of the mean,
SSexp is the SS of equation [24],
and SSlin is the SS of the linear function. [27]

The regression parameter of the linear function is, of course, also recorded.

Finally, a residual time series is calculated by subtracting the fitted IMAX model trend function from the observed time series. This residual time series, then, is partitioned into 5 consecutive subseries of 8 blocks of trials each. The mean, variance and error rate are calculated for each of these subseries. These variables serve the purpose of finding a trend in the residual time series.

3.7.5 Analysis

The central question throughout this thesis is: *Does the inhibition theory hold?* More specifically the predictions of the INHIBITION model are tested, such as an increase in the RTs, and an increase in $RT_{Variance}$.

Individual time series. If all the assumptions of the INHIBITION model would hold, an increasing RT curve is expected for each subject in a condition with a massed administration of trials. Therefore, the numbers of increasing and decreasing RT curves are always reported for each massed condition. It is also indicated whether the trend is statistically significant.

An indirect check on the constancy of the processing time is the test of a trend in the error rate. Given the number of errors per 8 blocks of trials the contrast of the first against the other four sub-series is tested. A failure to reject the null-hypothesis is in accordance with the constancy assumption (given that the power of the test is sufficient). However, also an increasing trend does not contradict the inhibition theory. On the contrary, if the error rate increases together with an increasing RT curve, this would support the theory a fortiori. The reason is that an increasing error rate implies a non-increasing processing time. This means that an observed increase in the RTs accompanied by an increase in the error rate can only be explained by an increase in the distraction time. If increasing error rate is due to a shift in speed-accuracy trade-off, i.e. a decreased processing time, we will obtain an underestimation of the distraction time.

The predicted increase in $RT_{Variance}$ is tested using the five parts of the residual time series. As this increase is expected mainly at the start of the time series, the contrast of the first versus the other four parts should serve as the test of an increasing variance.

Average time series. Of each condition a RT curve can be obtained by averaging the individual time series over subjects. These average time series of the conditions can, however, only serve the purpose of illustrating the dominating effects in the data. The average RT curve can, for instance, be predominately increasing, or the curve may show to be about stationary. But again, no tests will be performed at this level, since it is well-known that averaging over subjects can lead to artificial effects.

RT task variables by conditions. Depending on the specific experimental conditions predictions are formulated concerning the effects on RT_{Mean}, $RT_{Variance}$, $RT_{Minimum}$, and the error rate. These effects are tested with the usual analysis of variances. For instance, larger values on RT_{Mean} and $RT_{Variance}$ are expected in a massed condition than in a spaced condition.

Due to the fact that the IMAX model parameters are not meaningful in case of the spaced and the mixed conditions, nor in case of decreasing RT curves, ANOVAs on model parameters were not reported. As will be explained in the sequel parameter A is approximated by $RT_{Minimum}$. Therefore, effects on the processing time, A, are indicated by the ANOVA results on $RT_{Minimum}$.

3.8 Concluding remarks

The crucial assumption of the inhibition theory is that the tendency to shift from processing to distraction increases with the processing time and decreases with the distraction time. The INHIBITION model, a mathematical description of the inhibition theory, predicts an increasing RT curve accompanied by an increasing RT variance. For fitting the observed RT curves to the predicted curve the IMAX model is used as an approximation. The IMAX model predicts an increasing RT curve which is empirically hardly distinguishable from the RT curve predicted by the INHIBITION model. The final step in connecting theory and data is the description of the experimental paradigm for gathering the data.

Ideally, estimated INHIBITION model parameters should be used to test the inhibition theory. Given the problems described in this chapter, we had to be satisfied with a less ideal situation. Still, we are convinced that using a model in this situation is better than using no model at all to test the inhibition theory.

4 DISTRACTION TIME: MASSED VERSUS SPACED

The study presented in this chapter replicates findings of Van Breukelen and Jansen (1987a) concerning the role of distractions and inhibition in response times, but using a different task. The inhibition theory states that a fair amount of the reaction time consists of distraction time and that the tendency of being distracted increases during mental processing time and decreases during distraction. An experimental comparison of massed (continuous work) versus spaced (work with regular resting periods) served to test the two main hypotheses. Subjects were 16 male and 16 female student volunteers. A digit addition task was used. The experimental setting was as in Van Breukelen and Jansen (1987a). Specific predictions were derived from the INHIBITION model of Van der Ven, Smit, and Jansen (1989) as outlined in the previous chapter. The results supported most of these predictions.

4.1 Introduction

Distraction time and processing time are the essential concepts of the inhibition theory, which was introduced in the previous chapters. The inhibition theory consists basically of two hypotheses: (1) a considerable part of the observed RT is distraction time, and (2) the tendency of being distracted increases with the accumulated time of processing and decreases with the accumulated distraction time.

The aim of this chapter is to test these two hypotheses employing the massed versus spaced paradigm. As reported in chapter 2, massed and spaced were already employed as experimental conditions in the work of Hylan and Kraepelin (1904) and, more importantly, in the work of Bills (1931). The conclusion of both these studies was that rest periods as given in a spaced condition, have a beneficial effect on task performance. The present study differs in two respects from these earlier investigations: (1) a theory is presented which explains the improvement due to rest periods, and (2) specific predictions are derived from a mathematical formalization of this theory.

The experimental paradigm can be introduced as follows. In a massed condition the experimental trials are presented with a negligible response stimulus interval. This implies that the next stimulus is presented immediately after the subject's response. In a spaced condition periods of rest are given after each block of trials. The block size may vary from experiment to experiment, but the purpose of these rest periods remains always the same: a reduction of mental fatigue, i.e. a reduction of inhibition. The subject is allowed to extend his rest periods as much as he wishes. If distractions serve the purpose of reducing mental fatigue, as was supposed by Bills (1931) and others (e.g. Bertelson & Joffe, 1963), distractions will become superfluous once regular periods of rest are administered. Whereas an increasing RT curve is predicted by the INHIBITION model for the massed condition, a stationary (and faster) RT curve is predicted for the spaced condition.

By the time that the experiment reported in this chapter was run, the IMAX model was not yet developed. Therefore, no reference to this model is made in this chapter. The data are fitted to the INHIBITION model. Whenever it was not possible to obtain the exponential model of equation [15], a linear function was fitted in order to indicate whether the RTs were increasing or decreasing.

Predictions. The predictions for the massed versus spaced paradigm were already described in detail in chapter 3. At this place we will give a brief recapitulation of these predictions. For details, the reader is refered to the previous chapter. The predictions are:

(1) RT curves in a massed condition will be more increasing than in spaced conditions,

(2) the RT variance in a massed condition will be more increasing than in a spaced condition,

(3) distraction time will be larger in a massed condition than in a spaced condition,

(4) RT_{Mean} will be larger in massed conditions than in spaced conditions, and

(5) $RT_{Variance}$ will be larger in massed conditions than in spaced conditions.

Some empirical evidence. Comparing massed with spaced conditions, Van Breukelen and Jansen (1987a) already found an exponentially increasing trend in the expectation and variance of the RTs in the massed conditions and no such trend in the spaced conditions, as predicted by the INHIBITION model. These results support both the hypothesis predicting a considerable amount of distraction time and the hypothesis predicting an increasing inhibition to work. The estimated proportion of distraction time per RT was about 20% in the massed condition against 15% in the spaced condition. In another experiment of Van Breukelen (see Van Breukelen, 1989b, ch.5) the reduction of distraction time was from 25% in the massed condition to 15% in the spaced condition. The estimated proportion of distraction time per RT in Pieters' (1985) experiments was about 70%, which indicates that the PE model is probably less appropriate for these kinds of tasks.

More specifically, the aim of the present chapter, then, is to replicate the Van Breukelen and Jansen experiment using a different task. Instead of a cancellation task (a computerized Bourdon test) a digit addition task is used. This task was originally designed by Pauli (see Arnold, 1975). The experiment of Van Breukelen and Jansen will from here on be called the Bourdon experiment, whereas the present experiment will be referred to as the Pauli experiment.

A second aim is to explore the task independence of speed, precision and concentration. It seems worthwhile to explore to which degree mental speed and concentration can be considered as general properties of a subject's performance abilities. Task independence can be investigated because most of the subjects in the Bourdon experiment also participated in the present experiment.

Speed is defined as the inverse of the processing time per task unit, precision as the percentage of correct responses, and concentration as the ratio of the processing time to the mean RT. In chapter 8, another measure of concentration will be proposed. The correlations between the two tasks with respect to these variables indicate the degree of task independence of the subject's speed, precision and concentration.

4.2 Method

4.2.1 Subjects

Subjects were 16 male and 16 female student volunteers, aged between 18 and 30, from the Catholic University of Nijmegen. They were paid 8 guilders for participating. The experimental session took about one hour per subject.

4.2.2 Apparatus and Presentation

A modification of the Pauli test (Arnold, 1975), a digit addition task, was administered in a two-choice reaction time (2-CRT) format. The sum of each individual addition was less than 10. An example of an item as it was displayed is: 3 + 4 = 7. Subject were asked to decide whether the addition was wright or wrong by pressing the

'YES' or 'NO' button. Of each stimulus there was a correct and an incorrect version. An example of an incorrect addition is: 3 + 4 = 6. Each response was immediately followed by the next trial. RTs were recorded on line. The presentation of the stimuli and the experimental circumstances for the subjects were the same as in the Bourdon experiment. This implies, for instance, that the stimuli were presented on a 30 * 30 cm display at a visual angle of 1.5 degree and a distance of about 80 cm.

4.2.3 Procedure

Subjects were instructed to work fast, but without making errors. It was emphasized that errors could not be corrected. No feedback was given on either RT or errors.

Subjects had to complete a total of six series of 256 trials each. First, a practice series was given, followed by a global feedback and, if necessary, an instruction to work faster or more precise. The second series served as a baseline condition. Series three to six made up four experimental conditions:

1. **The massed condition.** This condition was identical to the practice and the baseline series. All 256 trials were presented in a continuous flow. The instruction for the subjects was to work fast without making errors.
2. **The spaced condition.** In this condition a resting period of three seconds was given after each fourth trial. After three seconds the subject could prolong the resting period or continue work by pressing a button. Subjects were instructed to work fast without making errors and to concentrate during work. Before the actual series 16 practice trials were given to acquaint the subject with the spaced procedure.

For explorative reasons two other conditions were added to the design. First, we added a condition with a time-limit. In practice, most tests which are constructed with the intention to measure concentration or intelligence, have a time-limit. It is, however, not exactly known what the effect is of such a time-limit. In the specific case of the present experiment, the subjects receive an incentive to give more correct answers within the same amount of time compared with the baseline condition. Are the subjects able to work faster without making more errors? Or do they work at the same speed but more precise? From the point of view of the inhibition theory, subjects could be able (up to a certain degree) to work as efficiently as possible by reducing the distraction time. They would, however, still show a performance decrement over time.

3. **The time-limit condition.** The presentation of the stimuli was identical to the massed condition. The instruction, however, was different. The subjects could gain a bonus of f2.50 by giving more correct responses than in the baseline condition within the same time. So, the time spent on completion of the baseline condition served as the time-limit. If they tried to give more correct responses within the time-limit, subjects could choose between working faster at the expense of relatively more errors, or working more precise but completing relatively fewer items within the time-limit. Subjects were given no suggestions for using a particular strategy. Furthermore, they received no feedback during the experiment.

The effect of item-difficulty by a carry versus no-carry factor was already tested by Pieters using the PE-model. This factor has not been investigated using the INHIBITION model. The effect of item-difficulty should be that parameter A becomes larger, and that, therefore, both the distraction time and the RT variance are larger in the carry condition.

4. **The carry condition.** This condition is identical to the massed condition except that in this condition the task is more complex. The digit additions have a sum between 10 and 20. Before the actual 256 trials of this series 16 practice trials were given. Whereas the contrast of massed versus spaced was used, as was explained previously, to test predictions concerning the distraction time, the carry condition was chosen to test the prediction that item-difficulty has an increasing effect on the processing time, A.

The four conditions were administered according to a latin square design to counterbalance their presentation order across subjects. Between conditions a resting period of approximately one minute was given.

4.3 Results

The results of the Bourdon experiment were essentially replicated, i.e. the predictions concerning the distraction and the inhibition hypotheses were confirmed, but like in the Bourdon experiment no clear autocorrelation was found. Further, a first indication for the task independence of speed, precision, and concentration was obtained.

4.3.1 Preliminaries to the data analyses

Starting effects after a rest period are well-known. Because rest periods were given after each fourth trial in the spaced condition, and because 8 consecutive trials were taken as the task unit (the block size) of RT analysis, the first and the fifth trial RT were left out of the analyses. This implies that the unit for the RT analysis was the sum of six trial RTs. These dummy trials (the first and fifth trial per block) permitted to control for stimulus and response effects and to equalize at the same time the blocks as much as possible. Using equivalent blocks of trials as the task unit was our strategy to meet the requirement that the processing time was about the same for all blocks of trials. Since each experimental condition contained 256 trials, 32 RTs per subject per condition were used in the RT analyses.

Trial RTs below 300 msec and standardized RTs below -3 or above 4 were classified as outliers and replaced by the subject's mean trial RT of the condition. The percentage of outliers per condition was 1% or less. One time-series contained 3% outliers. All other series contained 2% or less outliers.

The overall percentage of errors was 2.6%. Each time series contained 192 RTs (the dummy trials are neglected here). So there was an average of about five errors per time series.

4.3.2 Massed versus Spaced: Trend analysis

The exponential trend in the RTs. As explained in the introduction a low value of the inhibition at the beginning of the time series induces an exponentially increasing trend in the RTs. Although a decreasing trend does not contradict the model, only an increasing trend is expected, since the initial inhibition is assumed to be lower than the stationary inhibition.

Performing an exponential trend analysis on the individual time series gives the results shown in table 2. The exponential trend was fitted according to equation [15] of chapter 3. In the massed condition and in the time-limit condition almost all time series show an increasing exponential trend. In the spaced condition and in the carry condition far more time series have a decreasing than an increasing exponential trend.

TABLE 2

Number of Increasing or Decreasing Exponential Trend per Condition

Condition	Exponential Trend Curves	
	Increasing	Decreasing
Massed	30 (15)	2 (0)
Spaced	9 (2)	23 (5)
Time-Limit	29 (9)	3 (1)
Carry	10 (3)	22 (9)

Note. Total number of curves per condition = 32.
In brackets: significant trend curves (5% level)

In figure 5 the average time series of the four conditions are plotted. The RTs of the massed and the time-limit conditions show a clear increasing trend. The RTs of the carry and the spaced conditions show a decreasing trend. It should be noticed that averaging over subjects can have a deluding effect. Therefore, figure 5 only serves the purpose of an illustration.

The increasing exponential trend curve explained 74% of the variance of the average time series in the massed condition and 60% of the variance in the time-limit condition. In the spaced and the carry condition these percentages were 34% and 39% respectively. In these latter two cases it was a decreasing exponential curve.

Trend in residual RT variance. According to the inhibition hypothesis an increasing trend in the expectation of the RTs is due to a low initial inhibition, and should be accompanied by an increasing residual variance. To test this prediction the residual time series per subject per condition were constructed by eliminating the exponential trend from the actual RTs. The residual time series was then partitioned into four consecutive segments of 8 blocks of trials each. In each segment the residual mean and the residual variance were calculated. Per condition a MANOVA was performed with either the four means or the four variances as the dependent

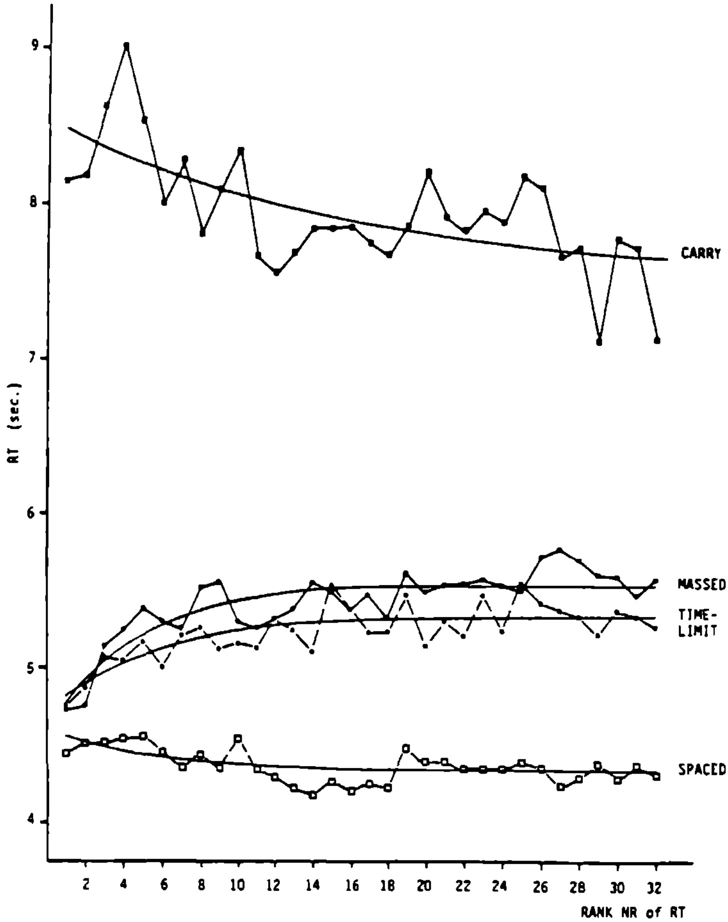


FIGURE 5

The average RT curves of the four conditions (N=32)
(the curves are fitted to equation [15] of ch. 3)

variables. The predicted increase of the residual variances was tested by the contrast of the first segment versus the other three. The results are shown in figure 6.

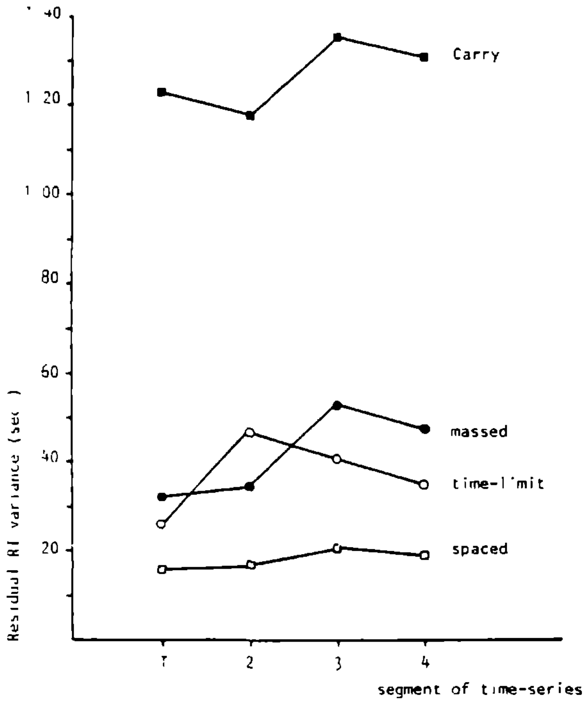


FIGURE 6

The Residual Variances per Condition and Segment

A significant increase of the residual variances was found in the massed condition with 0.32 for the first segment and 0.46 as the mean for the latter three segments, $F(1,31)=4.95$, $p<.05$, and in the time-limit condition with 0.27 against 0.42, $F(1,31)=7.14$, $p<.01$. No increase was found in the spaced and the carry condition. The contrast of the first block against the other three was taken as the indication for an increase. It seems that the residual variance decreases from segment 3 to segment 4 (see figure 6). The contrast of the third against the fourth segment is, however, not significant. In three of the four conditions the F-ratio of this particular contrast is even smaller than 1.

The overall multivariate tests on differences between residual means did not yield a significant effect in any of the four conditions, which implies that eliminating the exponential trend was sufficient.

The autocorrelation. A coefficient for the autocorrelation can not be measured directly, because trend in a time series induces a positive autocorrelation, whereas trend elimination artificially induces a negative autocorrelation of the residuals.

Two procedure were tried to yield some insight in the size of the autocorrelation of the observed time series. The first procedure selected time series that had no significant trend (at the 5% level). In the second procedure only the last 24 RTs of each time series were taken into consideration. Thereupon, again only those time series were selected which showed no significant trend. The reason for applying this second procedure was that most time series become stationary after the first 8 blocks of trials. Both procedures tend to the conclusion that no negative lag 1 autocorrelation is present in the time series of all four conditions (see table 3).

4.3.3 Massed versus Spaced: RT analysis

Due to the resting periods of the spaced condition and the learning effect in the RTs of the carry condition (see below) the INHIBITION model parameters can not be estimated in these conditions. Due to estimation problems in 25% of the time series of the massed condition and of the time-limit condition,[6] we refrain from analyses on the model parameters and only deal with RT_{Mean}, $RT_{Minimum}$, $RT_{Variance}$, residual RT variance and the number of errors. Since the mean distraction time (D) can be estimated by (RT_{Mean} - $RT_{Minimum}$), D is also used as a dependent variable.

A mixed model ANOVA was performed with Sex as between subjects factor and Condition and Sequence as within subjects factors. The levels of the Condition factor are the four experimental conditions. Sequence contains the four sequences of presentation (latin square factor). Three simple contrasts were tested on the factor Condition, i.e. the massed condition was contrasted with the spaced, time-limit and carry condition respectively.

As in the Bourdon experiment no Sex effect is found on any of the dependent variables. Only on the number of errors a slight Sequence effect is found,

[6] These problems have to do with the values of θ from equation [15] of chapter 3 that are very close to zero, or very close to one. For a specific discussion of this problem the reader is referred to Van der Ven, et al. (1989).

TABLE 3
The lag 1 autocorrelation for the time series without significant trend.

Condition	with dummy	without dummy
Massed		
32 RTs	0.071 (17)	0.036 (17)
24 RTs	0.029 (30)	-0.022 (25)
Spaced		
32 RTs	0.041 (28)	0.100 (28)
24 RTs	-0.002 (28)	0.019 (25)
Time-limit		
32 RTs	0.000 (20)	0.037 (23)
24 RTs	0.015 (30)	0.018 (27)
Carry		
32 RTs	0.083 (19)	0.095 (20)
24 RTs	0.010 (26)	0.029 (28)

NOTE. Between parentheses: Number of time series without exponential trend

$F(3,84)=2.82$, $p<.05$. The error rate increased from about 4.5 in the first two presented conditions to about 5.5 in the last two conditions. Also, no interaction effect is found except for a Condition by Sex effect on the number of errors, $F(3,84)=4.20$, $p<.01$ (see figure 7), which will be commented on below.

Of more interest for the present purpose are the condition effects, especially the contrast massed versus spaced. One of the predictions was that RT_{Mean} is lower in the spaced than in the massed condition. This prediction is strongly confirmed, $F(1,84)=26.63$, $p<.001$ (see table 4). Moreover, the number of errors, D, and $RT_{Minimum}$ are significantly lower in the spaced condition (see table 4). In addition, table 4 shows that the residual variances are higher in the massed than in the spaced condition, as was predicted.

TABLE 4

Means and F-values per condition and contrast

VARIABLES	MEANS		F	Sign. of F
	Massed	Spaced	(1,84)	
RT_{Mean}	5.42	4.37	26.63	$p < .001$
Resid.Var.	0.49	0.22	4.88	$p < .05$
$RT_{Minimum}$	4.22	3.62	20.88	$p < .001$
D	1.20	0.75	17.39	$p < .001$
Error Rate	5.22	4.03	4.58	$p < .05$
	Massed	Time-limit		
RT_{Mean}	5.42	5.24	0.79	$p > .05$
Resid.Var.	0.49	0.45	0.14	$p > .05$
$RT_{Minimum}$	4.22	4.23	0.01	$p > .05$
D	1.20	1.01	2.99	$p > .05$
Error Rate	5.22	4.44	1.99	$p > .05$
	Massed	Carry		
RT_{Mean}	5.42	7.95	155.00	$p < .001$
Resid.Var.	0.49	1.55	68.06	$p < .001$
$RT_{Minimum}$	4.22	5.78	144.48	$p < .001$
D	1.20	2.17	78.32	$p < .001$
Error Rate	5.22	6.88	8.88	$p < .001$

NOTE. Resid.Var. = the residual RT variance

$D = RT_{Mean} - RT_{Minimum}$

Massed versus Time-limit.

No statistically significant effect of massed versus time-limit is found on any of the five dependent variables (see table 4). However, both the number of errors, and D, tend to be lower in the time-limit condition, whereas $RT_{Minimum}$ is about equal for these two conditions. These results suggest that subjects are able to reduce their distraction time only a little, when forced to do so.

As mentioned before, a Condition by Sex effect on the number of errors is found. This interaction effect is foremost due to a sex difference in the time-limit condition. Although female subjects make generally more errors than male subjects, they make considerable fewer errors in the time-limit condition than the male subjects (see figure 7). Surprisingly, a similar, though not significant, interaction effect is found on D (see also figure 7). The processing time, estimated by $RT_{Minimum}$, is about the same in the two groups within each condition. This relation between D and the number of errors later will be considered in some extent in the discussion of this chapter.

Massed versus Carry.

In the carry condition the items are more complex than in the other conditions. By contrasting the massed and carry conditions the hypothesis is tested that item difficulty effects the processing time, which is estimated by $RT_{Minimum}$. A very significant difference between carry and no-carry (massed) is found on $RT_{Minimum}$ (see table 4). Furthermore, the carry condition shows significantly higher values than the massed condition on all other variables, including the number of errors (see table 4).

4.3.4 Learning effects

The Carry condition. The decreasing trend curve in the carry condition is thought to be a learning effect, because different stimuli (i.e. more difficult digit additions) were used in this condition, and because subjects got only 16 trials for practice. To test this hypothesis the two pre-experimental conditions were analyzed. It was predicted that the trend in the practice condition would be decreasing, like the trend in the carry condition, whereas the trend in the baseline condition would correspond more to the trend in the massed condition and be increasing. This prediction was tested for both the present and the Bourdon experiment.

The fitted RT curves of the practice and baseline conditions are shown in figure 8. The practice conditions show a clear decreasing trend, as predicted, whereas in the baseline conditions the trend is predominantly increasing.

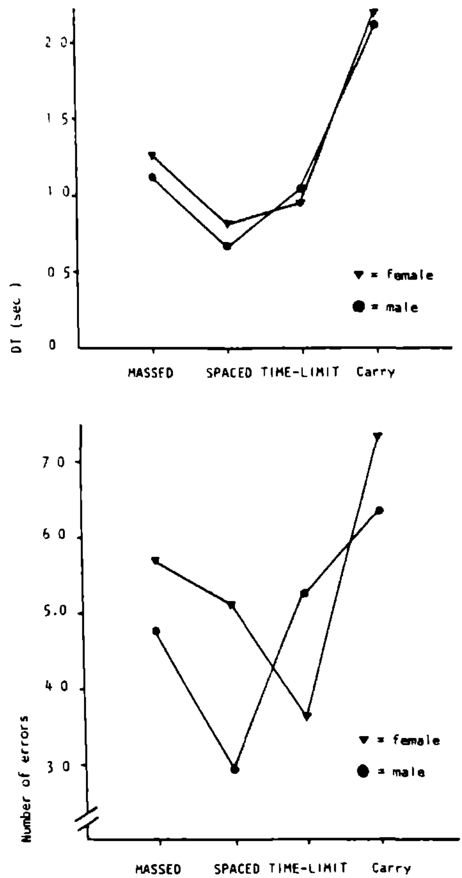


FIGURE 7

The Sex by Condition Interaction for Error rate and D

Trend analysis on the individual time series yields globally the same results. In the practice condition of the present experiment only 4 out of 32 individual time series show an increasing trend, whereas in the baseline condition 26 out of 32 time series have an increasing trend. For the Bourdon experiment the figures were 13 out

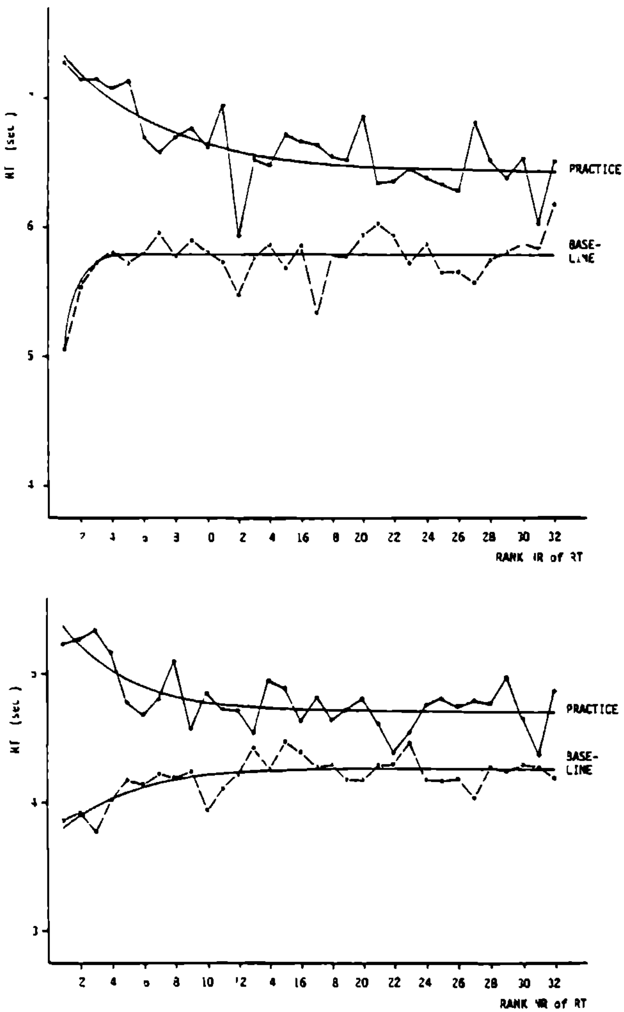


FIGURE 8

Fitted RT curves of Practice and Baseline for Bourdon (below) and present (above) experiment

of 39 in the practice condition and 32 out of 40 in the baseline condition.

The Spaced condition. As shown in table 2 a majority of the time series in the spaced condition are decreasing, as is the average time series. This suggests a small learning effect in this condition too, although in this case it would be learning the task-procedure instead of the task-stimuli. We, therefore, reanalyzed the data of the Bourdon experiment with respect to the spaced conditions.

Van Breukelen and Jansen (1987a) had four experimental conditions by crossing a massed versus spaced factor with a bonus (for speed) versus nobonus factor. So a spaced condition was administered twice (once bonus, and once nobonus). Moreover, the sequence order of administering the conditions was balanced over subjects. Averaged over subjects the first administered spaced series, which consisted of an equal number of bonus and nobonus conditions, is definitely decreasing (the decreasing exponential trend curve explains 12% of the variance), whereas the second spaced series is very slightly increasing (the increasing trend curve explains less than 1% of the variance).

4.3.5
Trend of RTs within blocks in the Spaced conditions

A resting period was inserted after each fourth trial in the spaced condition of the present experiment. The following analyses will be done on these four trials per block. First, we arranged a data set, in which the RTs per trial were averaged over subjects. Next, ANOVAs were performed on a design with the 4 trials as one factor and the 64 blocks as the cases. It turned out that the RT of the first trial in a block is significantly higher than the other three RTs, the mean RTs were 787, 736, 728, 731 msec. respectively, $F(1,63)=14.61$, $p<.001$. The first trial was used as a dummy trial. Our presumption that an 'adjusting' effect at the beginning of each block might occur, seems justified. Among the other three RTs no difference was found.

A similar analysis was also performed with respect to the spaced conditions of the Bourdon experiment. In that experiment a block consisted of 7 trials. In both the bonus and the nobonus condition the first trial RT is significantly higher than the other six trials, $F(1,39)=64.11$, $p<.001$, and $F(1,39)=43.22$, $p<.001$ respectively. The means of the trial RTs are given in table 5. An increase in the RTs was found in the last three trials of a block. A linear contrast on the last six trials yields in both conditions a significant effect, i.e. $F(1,39)=31.44$, $p<.001$, for the spaced nobonus condition, and $F(1,39)=24.07$, $p<.001$, for the spaced bonus condition (for the mean RTs see table 5).

TABLE 5

The means of the trial RTs within the (trial) blocks of the Spaced conditions of the Bourdon experiment

Condition	Trial Number						
(Spaced)	1	2	3	4	5	6	7
Nobonus	699	580	595	580	602	604	619
Bonus	674	559	570	555	582	578	594

RTs are given in milliseconds.

These results suggest that distractions emerge after four trials. It is tempting to state that the inhibition attains after four trials a certain critical level that makes the occurrence of distractions possible.

4.3.6 Task independence of subject variables

As the subjects of the present experiment also participated in the Bourdon experiment, it was possible to obtain some information on the task independence of mental speed and concentration by correlating measures of performance between the two experiments.[7)]

Analyses were performed on the corresponding task conditions, i.e. the baseline, massed and spaced condition. The corresponding practice conditions were only considered in the analysis on a measure of learning speed.

Mental speed was equated with the inverse of the processing time. In order to define estimates for the processing time, A, some assumptions have to be made. The following assumptions appear justified within the context of the model, although some of them may not be correct. This leads to various estimates of A:

[7)] In fact two more subjects were available for this analysis. These subjects were left out of the other analyses to obtain a completely balanced latin square for the presentation order of conditions.

a) Assume A is a constant per condition per subject, then A can be estimated by $RT_{Minimum}$ of the condition considered.
b) Assume A is constant within and across conditions, then A can be estimated by $RT_{Minimum}$ of the spaced condition. The idea in this case is that the $RT_{Minimum}$ of the spaced condition is a less biased estimator of A than the $RT_{Minimum}$ of the massed condition, which is assumed to contain more distractions.
c) Assume A is not strictly constant, and that the distraction time is negligible in the spaced condition, then A can be estimated by RT_{Mean} of the spaced condition.

Alternative (c) seems to be the least prone to bias, considering the relatively small variance in the spaced condition. However, in the sequel of this thesis only $RT_{Minimum}$ will be used as the estimator for the processing time. The reason is that this estimator is most in line with the INHIBITION model and the inhibition theory, since the INHIBITION model only applies to massed conditions.

Some correlations. The correlation of the processing time between the present and the Bourdon tasks is about .7 for all three estimates. The correlations of the distraction time range from .5 to .8 for the different experimental conditions (see table 6).

Precision defined as the number of correct responses correlates about .40 between tasks and conditions. Concentration defined as the ratio of the processing time and RT_{Mean} correlates about .70 and speed defined as the inverse of the processing time about .75 (see also table 6). It should be mentioned that with 34 subjects a correlation of .40 is already significant at the 1% level (df=32).

It was also investigated, whether learning speed (conceived as an ability) was task independent. This analysis was performed on the two practice series and the carry condition. The slope of the linear trend equation was taken as the estimate of learning speed. The two practice conditions correlate .67, whereas the carry condition correlates .64 with the Bourdon practice condition and .66 with the present practice condition.

4.4 Discussion

The inhibition theory was confirmed by the presence of trend in the RTs and in the variances of the RTs in the massed condition and their absence in the spaced condition. As in the Bourdon experiment, RT_{Mean}, $RT_{Minimum}$, D, the residual RT variance

TABLE 6
The Correlation between Pauli and Bourdon for Several Subject Measures

Variables	Task Conditions: Baseline	Massed	Spaced
Processing Time (A)	0.63	0.78	0.63
Speed (1/A)	0.71	0.85	0.67
D $(RT_{Mean} - A)$	0.76	0.53	0.72
Concentration (A/RT_{Mean})	0.68	0.41	0.63
Precision (Number correct)	0.37	0.48	0.40

NOTE. $A=RT_{Minimum}$ of condition considered

and the number of errors, had significantly lower values in the spaced condition than in the massed condition. This also corroborates the inhibition theory. However, no negative first lag autocorrelation was found. Together with the very slight negative autocorrelation found in the Bourdon experiment this means that the INHIBITION model has a weak spot in this respect.

The results of the contrast of massed versus time-limit showed that subjects are only partly able to reduce their distraction time. Basically, the time-limit condition stays a massed condition, in the sense that the inhibition mechanism necessitates also in this condition a decrement in performance.

An item difficulty effect on the processing time was predicted and found. So, even in simple mental tasks a considerable effect on the processing time is induced by an at first glance only slightly more difficult task. To evaluate this difficulty effect more thoroughly it is necessary to get in each condition time series without dominating learning effects.

4.4.1 The interruption hypothesis

The results indicate that the processing time is not constant across conditions, because $RT_{Minimum}$ and the number of errors are lower in the spaced condition than in the massed condition. Van Breukelen and Jansen (1987a) also found that the Spaced factor showed a decreasing effect on both $RT_{Minimum}$ and the error rate.

The decreasing effect on $RT_{Minimum}$ and the number of errors in the spaced conditions can be explained by assuming that distractions interrupt the solution process and demand more processing time to retain the same precision. This will be called the interruption hypothesis. In other words: distractions make it necessary to recheck parts of or the whole solution process, if one does not want to make errors. In this way the trade-off between processing time and the number of errors is affected by the distraction time. Therefore, it is possible that a spaced condition with almost no distractions has both a lower $RT_{Minimum}$ and a lower error rate than a massed condition, that contains a considerable amount of distraction time. It should be stressed that this hypothesis implies that the processing time is variable across and within conditions. It varies with the duration and the number of distractions. This does not invalidate the conclusions concerning the distraction and inhibition hypothesis, but it means that the INHIBITION model needs to be modified.

An indication for the interruption hypothesis is found in the group of female subjects. For these subjects both D and the number of errors are lower in the time-limit condition than in the massed condition, while $RT_{Minimum}$ is the same for these conditions. This finding appears to indicate two things: (a) subjects can control total response time without increasing the number of errors, and without affecting the processing time, and (b) while maintaining the same processing time, the number of errors can decrease due to fewer distractions interrupting the solution proces.

A similar conclusion concerning the interruption effect of distractions on processing was drawn by Kahneman, Treisman and Burkell (1983). They found that speeded choice responses to a relevant stimulus are delayed by the simultaneous occurrence of other visual events, even in the absence of sensory interruption, discriminating problems or response conflict. They came to the conclusion that any change or new information competes for attention and must be actively excluded, at a cost in the mean RT and/or the number of errors.

In combination with the limited resource theory for mental processes (see e.g. Wickens, 1984) the ideas of Kahneman and Treisman (1984) could be interpreted as: irrelevant stimuli spontaneously and unavoidably divert a portion of the resources needed to process the relevant stimuli (see also Holender, 1987). A same conclusion could be drawn from the present results. The difference is that

Kahneman and Treisman refer to observable distractors, whereas in the present study no observable distractors are present. They are dealing with effects of external distractors on mental processes, whereas we are dealing with the effect of (internal) inhibition on mental processes.

4.4.2 Some secondary findings

Another finding of the carry condition concerns the already mentioned learning effect. For the present research project learning is a disturbing factor. It seems nevertheless promising to investigate individual differences in learning speed considering the high correlations of the measure of learning speed. Furthermore, future developments of the INHIBITION model should incorporate a learning effect on the processing time.

Also promising seems the investigation of the task independence of speed, precision and concentration. A problem to be solved, however, is the estimation of the processing time. It is suspected that the processing time is variable due to an interruptive effect of distractions. So it seems worthwhile to model the processing time as some stochastic process. Only then it seems to be possible to get proper estimates of speed and concentration. The correlations found are nevertheless of some importance. This applies even more if we consider that the true correlations are underestimated, since the observed correlations were not corrected for unreliability and differences in speed-precision tradeoff between conditions. The implication is that there are task independent individual differences in speed, precision and concentration.

Of importance in this matter is the tentative outline of a theory on intelligence test scores given by Roskam (1987). Subjects' parameters as mental speed, accuracy, resources, concentration and persistence are defined and their relations are described. The aim of the research project in the near future will be to get some grasp on these subject parameters in order to explain individual differences in intelligence testing scores.

5 DISTRACTION TIME: HOMOGENEOUS VERSUS MIXED [8)]

The domain of interest of this chapter is limited to continuous performance on simple two-choice reaction time (RT) tasks. It is generally found that the RTs, the RT variance and the error rate increase over trials. There is no simple explanation for these findings in terms of a speed-accuracy trade-off, nor in terms of some additive factor processing model. Evidently some time gets 'lost'. To tackle this problem the RT was split into two components: processing time and distraction time, which is time spent on other mental activities than those to solve the task. This is the basic assumption of the inhibition theory. The inhibition theory contains a mechanism that predicts an increase in RTs with time on task. In the experiments of this study a single task condition (the homogeneous condition) was contrasted with an alternating task condition (the mixed condition). Whereas most other theories would predict more decrement in RT performance in the more demanding mixed condition, the inhibition theory predicts a larger increase of RTs in the homogeneous condition. The results supported the inhibition theory. In the mixed condition the subjects lost less speed over the series of trials, made fewer errors, had lower RT variance and were on the average as fast as in the homogeneous condition.

5.1 Introduction

A decrement in reaction time (RT) performance in a condition with a continuous administration of well-practiced trials (a so-called massed condition) is consistently found across a number of different tasks and within different populations of subjects. In our own experiments (Van Breukelen & Jansen, 1987a; Jansen & Van Breukelen, 1987; Van der Ven, Smit & Jansen, 1989) the increasing RT curves in the massed condition were found using a dot counting task (the Bourdon task), a digit-addition task, and a letter-matching task with adults as well as with children, and even with paper and pencil tests administered in the school situation (Van Breukelen & Souren, 1990). Bertelson and Joffe (1963) and Sanders and Hoogenboom (1970) reported also the same kind of effects in massed series of their experiments. In a broader sense this impairment in performance is found in tracking tasks (Eysenck &

[8)] This chapter is a revised edition of Jansen, R.W. & Roskam, Edw.E. (1989). 'Mental Processing and Distraction' in: E.E. Roskam (Ed.) *Mathematical Psychology in Progress*. pp.133-156, New York: Springer.

Frith, 1977) and in vigilance tasks (Mackworth, 1969; Parasuraman, 1985). We hold the position that the same mechanism is responsible for the decrement in performance in each of the cases mentioned. Up till now no satisfying answer was given to the question concerning the structure of this mechanism.

An example of the kind of experiments showing performance decrement is an experiment of Van Breukelen and Jansen (1987a). The Bourdon task (see for the original version Bourdon, 1895) served as the simple mental task. In this task dot patterns are shown containing either three, four or five dots. Subjects had to respond YES on a stimulus with four dots, and otherwise they had to respond NO. After considerable practice subjects got a condition with a continuous series of trials (the massed condition) and a condition with regular rest periods between blocks of trials (the spaced condition). The results of this experiment were as follows. In the massed condition the RTs tend to increase over trials. It can be added that both the $RT_{Variance}$ and the error rate increase during the session. No such increase is found in the spaced condition. Further, the RT_{Mean}, $RT_{Variance}$ and the number of errors are lower in the spaced condition than in the massed condition. In figure 9 the average RTs (averaged over 40 subjects) per block of six trials are given for the two conditions mentioned. Moreover, the fitted RT curves according to the INHIBITION model are depicted for the massed and the spaced condition.

No obvious explanation can be given for this increasing RT curve. For example, taking into account that besides the RTs also the error rate increased, it becomes evident that a speed-accuracy trade-off can not explain the observed RT series in the massed condition. Further, an appropriate additive factor processing model can hardly be constructed in an attempt to cover this problem, since the two conditions were absolutely equivalent with respect to the stimulus and response administration. As a last example, one could mention fatigue as an explanatory factor (skipping for the moment the objection that a label by itself is not an explanation). However, fatigue would *not* be expected to be present at the start of the time series, and furthermore, once fatigue is present, one would expect an accelerating time series. The observed RT series is decelerating from the start.

5.2 Homogeneous versus mixed tasks

Monotony and boredom are two terms frequently encountered in the literature on ergonomics. They are relevant to situations in which people have to execute the

FIGURE 9

The massed versus spaced condition

(Rearranged from Van Breukelen et al., 1987b)

same kind of operations for hours and hours, but also to half-hour tasks of a repetitive nature in the laboratory (see for a review Davies, Shackleton & Parasuraman, 1983). In such monotonous and boring situations an impairment in performance is always observed. Davies et al. (1983) pointed out that no common definition of monotony and boredom exists.

Welford (1965) expressed that boredom should be associated with 'underload'. Typically boring situations seem to be those in which attention is required, but little information is conveyed. The association of boredom with underload serves to distinguish boredom from fatigue. The latter is regarded by Welford as resulting from chronic overloading of the sensory, central, or response mechanism involved in task performance.

Baschera and Grandjean (1979) drew the same distinction between monotony and fatigue, associating monotony with underload and fatigue with overload.

According to these authors the states of monotony and fatigue have in common that both produce impairment of performance and feelings of fatigue and sleepiness. A difference is that monotony is quickly reversible, while fatigue requires an adequate recovery period. They conclude from their experiments that repetitive tasks with a low degree of difficulty produce a state of monotony due to the lack of stimulation, whereas a repetitive task with a high degree of difficulty produces a state of fatigue due to a high mental load.

In the present study we are dealing only with well-practiced simple mental tasks. Such repetitive tasks are called *homogeneous tasks* [9] throughout this thesis, or monotonous tasks as Welford, and Baschera and Grandjean would call them. These authors put forward the concept of underload to explain the impairment of performance on such homogeneous tasks. From that point of view task performance would improve if the homogeneous task would be made more stimulating.

Whereas Welford (1965) and Baschera and Grandjean (1979) only describe and label the situation of monotony, the inhibition theory poses the mechanism that explains why performance on a homogeneous task decreases, and what conditions lead to better performance. For example, one could call alternation of tasks more stimulating, and one could predict that stimulation leads to better performance. However, this labeling of a stimulating situation again does not explain why performance will improve. In case of the alternation of tasks the inhibition theory will explicitly give the reasons for the improvement of RT performance.

5.3 Predictions

The aim of this chapter is to find additional evidence supporting the inhibition theory. This theory predicts performance decrement with time on task, as well as some other effects. Whereas in the previous chapter the massed versus spaced paradigm was used to test the theory, this time the homogeneous versus mixed tasks paradigm is taken as the basic design for experimenting.

As explained in chapter 3 the mathematical model approach is followed for deriving predictions. However, in order to avoid an extensive replication of the considerations for deriving predictions, we will present in this chapter the predictions only in

[9] As already mentioned the term 'homogeneous' is preferred to the term 'monotonous' to describe tasks containing only one kind of stimuli.

terms of the RT variables.

In the three experiments to be discussed homogeneous tasks and mixed tasks were administered in a massed version. Homogeneous means within this context that the subject is given only trials with stimuli of one kind of task, e.g. the Bourdon task. In the mixed task condition stimuli of two or three different tasks are alternated in a random order, e.g. alternating Bourdon trials with trials of a letter-matching task. It is important to notice that stimuli were presented self-paced with a negligible response stimulus interval in both task conditions. In this way subjects were forced to work continuously. Details of this experiment will be presented in a later section.

The inhibition theory. It states that the processors of the task relevant information will become inhibited because of the repetition of the required action. These processors need a recovery period. Assuming that information is processed at any time, it follows that while the task relevant processors are 'blocked', only task irrelevant information can be processed.

This line of reasoning leads us to the notion that another task can be executed within the period of time that the first task processor is inhibited. In figure 1 of chapter 3 the processors of the second task are indicated by P2 between parentheses. The processors of the first task can recover in the time consumed by the processors of the second task. The assumption is made that the two tasks have none or only a few processors in common. Therefore, this inhibition hypothesis predicts that the distraction time will be lower in the alternating task condition, since the two (or more) tasks work as each others distractions. The second task is irrelevant for the first task, but not irrelevant for the overall task performance.

Assuming that by alternating two tasks the second task gives relief to the processors of the first task just as a rest period would, the predictions for the massed versus spaced paradigm would mutatis mutandis hold for the homogeneous versus mixed paradigm. Therefore, referring to chapter 3, the following predictions can be given:

(1) RT curves in a homogeneous condition will be more increasing than in mixed conditions,

(2) the RT variance in a homogeneous condition will be more increasing than in a mixed condition,

(3) distraction time will be larger in a homogeneous condition than in a mixed condition,

(4) RT_{Mean} will be larger in homogeneous conditions than in mixed conditions, and

(5) $RT_{Variance}$ will be larger in homogeneous conditions than in mixed conditions.

An alternative theory: loss of attentional capacity. To show that the above mentioned theory is not at all trivial, an alternative theory is presented. In some experiments on vigilance tasks Parasuraman (1985) found that performance got worse especially in those conditions that had a high event rate. From these and other results he concluded that loss of attentional capacity is the factor responsible for the decrement in performance in vigilance tasks. In case of the homogeneous versus mixed tasks this hypothesis would state that the increase in RT would be largest in the condition with the largest demand for attentional capacity. Since in the mixed condition two task instructions have to be kept active in working memory, the prediction of this hypothesis would be that the decrement in performance would be larger in the mixed task condition.

To be specific, the loss of attentional capacity theory disagrees with the inhibition theory on all five predictions mentioned. In fact, it seems not too far fetched to state that this theory would predict just the opposite of the above mentioned predictions.

5.4 Experiment 2

5.4.1 Method

Subjects. Five male and seven female students volunteered as subjects for about two hours per person. They received each 16 guilders for their participation.

Apparatus. An Olivetti M28 Personal Computer was used along with a so-called APLEX interface card and a panel with three buttons, which was especially designed and manufactured for this kind of experiments. The screen was placed about 40 cm in front of the subject. The stimuli (letters, digits, or dot patterns) were white against a black background. The hue was determined by the subject during the practice session and held constant afterwards.

Design. Seven conditions were administered in a full within subjects design. These conditions consist of three homogeneous conditions, three mixed conditions of two alternating tasks (mixed-two conditions), and one mixed condition of three alternating tasks (the mixed-three condition). To keep the task for the subject workable, they received six of the seven conditions, i.e. three homogeneous conditions, two out of the three mixed-two conditions, and the mixed-three condition. The presentation order of these conditions was: first the homogeneous tasks, then the mixed-two conditions, and finally the mixed-three condition. Across subjects the sequence of the conditions was balanced as much as possible.

Procedure. The following tasks were used: 1) a letter-matching task, 2) the Bourdon task, and 3) a digit-addition task. This letter-matching task was introduced by Posner (1978). In this task stimuli are presented containing two characters. Both upper- and lowercase characters belong to the set of stimuli. In the Name match version of this task the subject is asked if both characters stand for the same Lexical symbol. In the Physical match version the subject has to respond to the question if the characters are identical with respect to their Physical appearance. For example, the combination 'A a' elicits a YES response under the Name match condition, but a NO response under the Physical match condition. The Name match version of the Posner task is used in all three experiments to be reported. The Physical match is only administered in experiment 3.

In the digit-addition task subjects are asked if the addition shown is correct or not. This task is a modification of the Pauli test (see Arnold, 1975). Hence, this task will be called the Pauli task.

Per condition two practice series of 120 trials were administered followed by the experimental series of 240 trials. In the alternating task condition the stimuli were presented quasi randomly. Every twelve successive trials consisted of six trials of each task, and every six successive trials consisted of three YES and three NO responses. Moreover, of each task all stimuli were presented before a stimulus could be presented a second time. Given these restrictions, the sequence order of the stimuli was chosen randomly.

RT was recorded per trial, but the analyses were performed on RT per block (see chapter 3 for explanation). A short coffee break was given after the first three conditions. Instructions were presented on the screen, just before every new condition.

5.4.2 Results

Figure 10 shows the fitted RT curve (fitted to the IMAX model) of the average time series of the homogeneous conditions and of the mixed conditions. Although this figure may be too global to state definite conclusions, the two curves are in line with the inhibition hypothesis, since the RT curves are less increasing in the mixed condition.

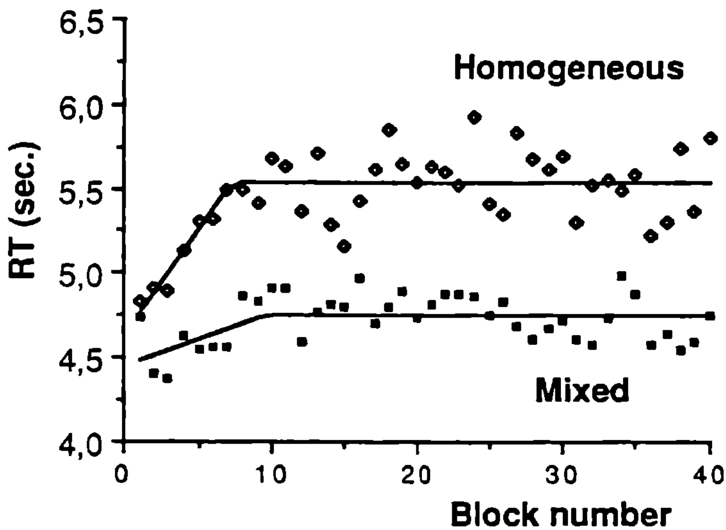


FIGURE 10
The fitted RT curves of the Homogeneous and the Mixed conditions.

The results, presented in the following sections, are treated in three respects. Firstly the average curves of the mixed conditions are split by task. Secondly the individual time series will be examined. And finally, analyses of variances will be presented with the RT variables (RT_{Mean}, $RT_{Minimum}$, error rate, etc.) as the dependent variables.

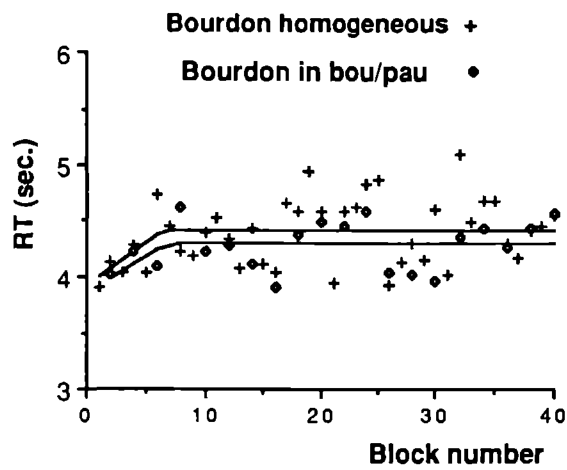
As described earlier, every condition contains 240 trials. In the mixed-2 conditions every 12 successive trials consisted of six trials of each task. Therefore, it was possible to decompose the time series of the mixed conditions into two reconstructed time series, one of each task. Taking again six trials for one RT, we got 20 RTs for each task in the time series. Since half of the trials (all belonging to the other task) are cut out of the original trial series, these 20 RTs should be plotted against the original horizontal axis of the total 40 blocks of trials. For example, figure 11 shows the reconstructed time series of the Bourdon trials out of the Bourdon-Posner condition (below) and the reconstructed time series of the Bourdon trials from the Bourdon-Pauli condition (above in figure 11). The homogeneous condition of the Bourdon task is also depicted in figure 11. The homogeneous condition is averaged only over those subjects who got the corresponding mixed condition. For instance, in the upper figure of figure 11 8 subjects had got the Bourdon-Pauli mixed condition. Of this mixed condition we reconstructed for each subject the Bourdon RT curve and averaged these curves over the subjects. From the same 8 subjects we took their Bourdon homogeneous time series and averaged also these series over the subjects. In this way we got the two curves as shown in the upper part of figure 11. The same procedure was followed for the lower part of this figure.

To give a fair comparison of the homogeneous versus the mixed conditions this figure has two interpretations of the horizontal axis. The 40 blocks of trials of the homogeneous condition cover the same range of trials as the 20 blocks of trials of the reconstructed Bourdon trials out of the mixed conditions.

So, in figure 11 the Bourdon RT curves of the homogeneous condition and of the reconstructed mixed conditions are shown. The RT curves of the homogeneous condition are in both cases more increasing than the reconstructed RT curves of the mixed conditions. The same pattern of trend curves was also found for the Pauli task and for the Posner task, in their comparisons of the homogeneous versus the reconstructed 'mixed' conditions.

The individual time series. We also fitted the IMAX model to each individual time series. If all homogeneous conditions on the one hand and all mixed conditions on the other hand are taken together, table 7 shows that more curves increase in the homogeneous conditions than in the mixed conditions. Table 7 also yields the results of the experiments 3 and 4 (discussed below) with respect to the number of increasing and decreasing individual time series. In all three experiments the homogeneous conditions have more increasing RT curves than the mixed conditions. The specific results of experiments 3 and 4 will be commented in a later stage.

Besides the RTs also the error rate increased. The mean error rate over the first 8 trial blocks (i.e. 48 trials) was 0.82 against 1.15 errors per trial block over the last



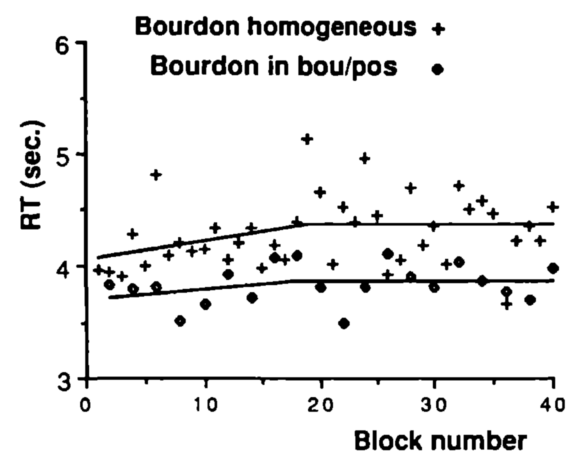


FIGURE 11

The fitted split Bourdon RT curves in the homogeneous versus mix with Pauli (above) and homogeneous versus mix with Posner (below)

32 trial blocks, $F(1, 70)=6.23$, $p<.05$. This increase in error rate was found in both the homogeneous and the mixed conditions.

TABLE 7

Number of increasing and decreasing individual time series for all three experiments

EXPERIMENT	CONDITION	INCREASING	DECREASING
2	Homogeneous	30 (7)	6 (1)
	Mixed	25 (4)	11 (1)
3	Homogeneous	27 (7)	9 (2)
	Mixed	4 (1)	20 (5)
4	Homogeneous	34 (12)	14 (2)
	Mixed	26 (2)	22 (5)

Note. Between brackets: number of significantly increasing or decreasing curves, where $F(2, df_2) = MS(\text{IMAX-model})/MS(\text{MEAN-model})$, $\alpha = .05$

TABLE 8

Mean RT variance per segment for both conditions

CONDITION	SEGMENT 1	2	3	4	5
Homogeneous	0.68	0.78	0.94	0.92	0.93
Mixed	0.56	0.76	0.73	0.73	0.67

It was predicted that the (residual) RT variance would increase more in the homogeneous condition than in the mixed condition. Table 8 showes that this prediction is at least partly supported. First of all, an overall increase in RT variance from the first to the latter four segments is significantly present, $F(1, 70)=26.17$, $p<.001$ (for the means see table 8). Secondly, a significant interaction is found for the contrast of the second versus the latter three segments. Whereas there is an increase of the RT variance for the homogeneous conditions, no increase is found for the mixed conditions, $F(1, 70)=8.84$, $p<.01$.

TABLE 9

Means and F-values per task variable in experiment 2

VARIABLES	Conditions		F	Sign. of F
	Homog.	MIXED	(df=1,50)	
RT_{Mean}	5.5	4.7	15.63	$p < .001$
$RT_{Minimum}$	4.07	3.58	14.05	$p < .001$
$RT_{Variance}$	1.12	0.71	6.80	$p < .05$
Error Rate	5.33	5.49	0.11	$p > .05$
DT/PT	0.34	0.31	5.50	$p < .05$

DT/PT = $(RT_{Mean}-RT_{Minimum})/RT_{Minimum}$

Homog.= Average across Bourdon, Posner, and Pauli (3 times N=12)

MIXED = Average across all MIXED2 (3 × (N=8)), and MIXED3 (N=12)

The ANOVAs. The parameters of the IMAX model only have acceptable values in case the time series increases. For instance, $I_{MAX}A/\delta$ (the expression for DT in the stationary part of the time series) will have a negative value if the time series decreases. In order to have acceptable values for DT and PT in case of decreasing RTs, some robust approximations of PT and DT are proposed. A robust (though slightly biased) estimator of PT is the $RT_{Minimum}$ (see Van Breukelen, 1989b). DT can, then, be expressed as (RT_{Mean}-$RT_{Minimum}$). Therefore, DT/PT can be estimated by (RT_{Mean}-$RT_{Minimum}$)/($RT_{Minimum}$), i.e. the distraction time per unit processing time. Since $RT_{Minimum}$ and DT/PT can be calculated for every time series these task variables will be taken into account in the following ANOVAs, and not the IMAX model parameters.

The ANOVA results are very clear-cut. The mixed conditions have significantly lower values than the homogeneous conditions (see table 9) on all task variables except for the error rate. To illustrate the amount of processing time and distraction time in the homogeneous and the mixed conditions table 9 also gives the average values of all RT variables.

TABLE 10

Means per condition for three RT variables

CONDITION	VARIABLES			
	RT_{Mean}	$RT_{Minimum}$	DT/PT	N
Homogeneous				
Bourdon	4.28	3.28	0.31	12
Pauli	7.49	5.38	0.38	12
Posner	4.65	3.47	0.34	12
Mixed-3				12
Bourdon	4.33	3.53	0.23	
Pauli	5.38	4.35	0.24	
Posner	4.35	3.46	0.26	

DT/PT = (RT_{Mean}-$RT_{Minimum}$)/$RT_{Minimum}$

N = Number of subjects per condition

For a more precise evaluation of the condition effects, table 10 shows for the mixed3 condition the values of three variables per separate task, in case we reconstruct the data by taking together the trial RTs for each task. Comparing these values as given in table 10, shows that it is not RT_{Mean} or $RT_{Minimum}$ that changes in a particular direction, but is the combination of the two as expressed by DT/PT that *decreases*. The interpretation might be that the gross speed of a subject is enlarged in the mixed condition due to a decrease in his distraction time.

It should be emphasized that DT/PT is a measure for the distraction time per unit of processing time. This means that the analyses on this measure are fairly independent of the analyses on PT, i.e. $RT_{Minimum}$. In fact, the correlation between $RT_{Minimum}$ and DT/PT was on the average near zero. The correlations between RT_{Mean}, $RT_{Minimum}$ and $RT_{Variance}$ are usually quite substantial, ranging between 0.6 and 0.8.

5.4.3 Discussion

The results of Experiment 2 support the inhibition hypothesis. On the average the RT curves of the homogeneous task increase more than those of the mixed conditions. The same accounts for the individual time series. The ANOVA on DT/PT shows that the proportion of distraction time is far greater in the homogeneous condition than in the mixed conditions. All these results are in conflict with the loss of attentional capacity hypothesis and are in line with the inhibition hypothesis. Distraction time becomes less when two tasks are alternated.

The fact that the $RT_{Minimum}$ is significantly lower in the mixed conditions than in the homogeneous conditions indicates a sequence effect. Subjects learn to do the task more efficient. However, reasoning in this way implies that the difference in distraction time found between homogeneous and mixed conditions could be even larger, since a learning effect is masked in the homogeneous conditions. Absence of that learning effect could lead to more detectable distraction time, because the estimated processing time would most probably be lower, and therefore the ratio DT/PT would be larger. The problem of a decreasing processing time has been handled elsewhere (Van Breukelen, Van den Wollenberg & Van der Ven, 1987c). For the moment, it should be recorded that the sequence effect in the presentation order may discredit the effects found in the ANOVA, but the conclusion that distraction time is larger in homogeneous conditions than in mixed conditions could be even more true.

5.5 Experiment 3

In Experiment 2 the sequence of the homogeneous and mixed conditions was not balanced across subjects. Therefore, a sequence effect might have caused the differences found on the task variables between these two conditions. A replication of the first experiment was done in which the presentation order of all the conditions was balanced across subjects.

5.5.1 Method

This experiment was divided into two parts. The first part contains a comparison between the homogeneous conditions of the Posner task and the Bourdon task, and the mixed condition of these two tasks. In the second part, a similar comparison was made using the Posner task and the Pauli task.

The comparison between the mixed Posner-Bourdon and their corresponding homogeneous conditions was of primary interest, because these conditions were completely balanced over subjects without any interference of any other condition. So, the Pauli condition and the Pauli/Posner mixed condition were added in a separate part of the experiment. These latter two conditions were given for more or less explorative reasons in the sense that in this part the mixed condition followed the homogeneous condition, comparable to the design of Experiment 2.

Twelve subjects who did not participate in Experiment 2, volunteered in Experiment 3 receiving a financial reward. The apparatus was exactly the same in this experiment as in Experiment 2.

Procedure. Firstly, all practice series were administered in a counterbalanced design within subjects. Two practice series in every condition had to be performed. After these practice series a short break was given. Thereupon the three conditions (Bourdon, Posner, and their mix) were administered in a completely balanced design across subjects. A second break was given followed by the Pauli condition and the mix of the Pauli task and the Posner task. All details of this experiment were the same as in Experiment 2.

5.5.2 Results

With respect to the average RT curves the results of Experiment 2 and Experiment 3 are about the same. Again the RT curves of the homogeneous conditions are increasing and those of the mixed conditions are even decreasing. This decreasing effect in the mixed task conditions is very well visible in table 7. This table shows that a vast majority of the curves of the mixed conditions are decreasing, whereas most of the curves of the homogeneous conditions are increasing (see table 7).

The error rates behave in the same way as the RTs. An increase in the error rate is found in the homogeneous conditions, 0.64 for the first segment against 1.07 for the latter four segments. The figures for the mixed conditions are 0.75 against 0.70, indicating a slight decrease. The interaction between this contrast and the two conditions is approaching significance, $F(1,55)=3.69$, $p=.06$

TABLE 11

Mean RT variance per segment for both conditions

CONDITION	SEGMENT 1	2	3	4	5
Homogeneous	0.44	0.56	0.52	0.48	0.51
Mixed	0.39	0.47	0.39	0.49	0.42

As predicted, also the RT variance increases from the first segment to the latter four segments, $F(1,55)=8.92$, $p<.01$. Table 11 shows that the differences in RT variance in absolute values is larger in the homogeneous conditions than in the mixed conditions, but this interaction is not significant.

The RT variables. The ANOVAs are quite different from those of the experiment 2. In the first part, in which the Posner task and the Bourdon task were compared with their mix, the $RT_{minimum}$ was much lower in the homogeneous conditions than in the mixed condition, $F(1,22)=17.7$, $p<0.001$ (the means are shown in table 12). A similar effect was found on the RT_{Mean}, $F(1,22)=6.6$, $p<0.05$.

TABLE 12

Mean values of the RT variables for each condition

VARIABLE	CONDITION				
	Bourdon	Pauli	Posner	Bou/Pos	Pau/Pos
RT_{Mean}	3.57	4.92	3.69	3.78	4.15
$RT_{Minimum}$	2.82	3.87	2.91	3.06	3.28
$RT_{Variance}$	0.24	0.47	0.30	0.25	0.27
DT/PT	0.27	0.27	0.27	0.23	0.27
Error rate	4.33	6.33	4.08	2.50	4.58

No other significant difference was found. Notwithstanding this fact, DT/PT is lower in the mixed condition, $F(1,22)=3.37$, $p=0.08$, as was predicted by the inhibition hypothesis. Part of the difference in the $RT_{Minimum}$ can be caused by the smaller error rate in the mixed condition. The means of all RT variables for each condition are shown in table 12.

In part two of this experiment, i.e. the comparison of the Posner and the Pauli task with their mix, there was no difference in RT_{Mean} or $RT_{Minimum}$ between mixed and homogeneous conditions, and only the $RT_{Variance}$ appears to differ significantly. The mixed condition had the lower value. This condition was the last one in the presentation order.

5.5.3 Discussion

Summarizing the results of Experiments 2 and 3 we get to the following conclusions. In Experiment 2 more individual time series are increasing in the homogeneous condition than in the mixed condition. The same holds for Experiment 3. Only in Experiment 3 time a vast majority of the RT curves in the mixed condition is decreasing.

In Experiment 2, RT_{Mean}, $RT_{Minimum}$ and $RT_{Variance}$ were much lower in the mixed conditions than in the homogeneous conditions. On the other hand, $RT_{Minimum}$ and

RT_{Mean} are much higher in the mixed conditions than in the homogeneous conditions in Experiment 3. Both experiments yield the same results with respect to DT/PT. This ratio is lower in the mixed condition as predicted by the inhibition theory.

Possible interpretations of these results are: (1) the effects found on RT_{Mean} and $RT_{Minimum}$ in Experiment 2 might be due mainly to a sequence effect, which is commonly labelled as learning, and (2) the design of Experiment 2 might have been very well chosen with regard to the requirement that a task should be overlearned. The mixed tasks of Experiment 3, however, clearly do not fulfill this requirement of being overlearned, as the majority of the RT curves is decreasing in that condition. The design of Experiment 3, therefore, might have more confounding factors than that of Experiment 2. The mixed conditions of Experiment 2 have a learning advantage over the homogeneous conditions, whereas the mixed conditions of Experiment 3 violate the assumption of overlearnedness of the task. In Experiment 2, however, the conclusions regarding the inhibition hypothesis hold a fortiori, whereas the conclusions in Experiment 3 are disputable.

Considering the shapes of the RT curves of the two conditions the conclusions of both experiments are in favor of the inhibition hypothesis stating that distractions occur because the processor of the task relevant information is inhibited. This hypothesis assumes that more than one processor operates in the human information processing system. During the period that the processor (of one task) is inhibited (the non-work period of that processor), the other processor can do its job in an alternating task condition. If, however, both tasks use mostly the same processors, then again the distraction time should be as large as in the homogeneous task condition. Experiment 4 attempts to test that hypothesis.

5.6 Experiment 4

The hypothesis tested in this experiment states that the distraction time of two alternating tasks which require the use of mostly the same processors will be larger than the distraction time of two tasks using different processors. This hypothesis follows directly from the inhibition hypothesis stated earlier. Schematically figure 1 of chapter 3 could be modified a bit for this purpose. In figure 12 the overlap between the processors of the two mixed tasks is illustrated.

This experiment was worked out in the following way. Two versions of the letter-matching task of Posner, i.e. the Name match and the Physical match, were both

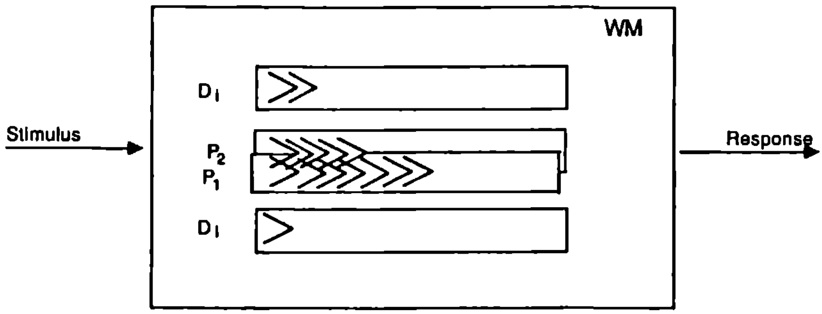


FIGURE 12

The cognitive model for the mixed task condition.

used in this experiment. Further, the Bourdon task and a Lexical decision task were used. The idea was that the Bourdon task, a dot counting task, uses at least partly the same (figural) processors as the Physical letter-match, and that the Lexical decision task uses at least in part the same (verbal) processors as the Name match of the Posner task. Further, we assumed that the Bourdon task and the Name match task had less processors in common than the Lexical decision task and the Name match task. In the same way we assumed that the Physical match task had more processors in common with the Bourdon task than with the Lexical decision task.

Assuming that the Bourdon task and the Physical match task employ partly the same mental processors, the mixed condition of these two tasks will increase the inhibition of the mental processors in the same way as a homogeneous condition. Therefore, the mixed Bourdon/Physical match condition will necessitate more distraction time than the alternation of the Physical match condition with a Lexical decision task. Mutatis mutandis the same reasoning accounts for the comparison of the

Name match/Lexical decision condition with the mixed condition of Name match and Bourdon.

The following predictions, then, can be formulated: (1) the condition of alternating the Bourdon task with the Physical match task will show more distraction time than the condition of alternating the Lexical decision task with the Physical match task, and (2) the condition of alternating the Bourdon task with the Name match task will show less distraction time than the condition of alternating the Lexical decision task with the Name match task.

5.6.1 Method

Subjects. Subjects were seven male and nine female student volunteers. They were paid about 16 guilders for their session that took less than two hours.

Task and Procedure. The Bourdon task and the Posner Name match task were already mentioned. The Lexical decision task consisted of the presentation of a word with the question if this was a correct Dutch word. The word length and the familiarity of the word were controlled. Only four to eight letter words were used. Familiarity of the words was checked by word frequency in the Dutch news papers (Uit den Boogaart, 1975, was used as the reference). The non-words were formed by changing one or two characters while keeping the word phonologically Dutch. The Posner Physical match had only a different instruction in comparison to the Posner Name match. This time subjects were asked only to match the characters on their shape. This means that the combination 'A a' has to be answered as different.

Subjects were partitioned into two groups of eight. The first group received the Posner Name match. The second group got the Posner Physical match. Both groups got furthermore the Bourdon task and the Lexical decision task. Within each group all possible mixed-two conditions were administered. The design of this experiment is depicted in table 13.

Table 13 shows that the homogeneous conditions were administered first, followed by the mixed conditions. These mixed conditions were counterbalanced within and across subjects. For that purpose the subjects received the relevant mixed conditions two times. The Bourdon-Lexical decision combination is the non-relevant mixed condition, since the hypothesis makes no statement with respect to this combination. This Bourdon-Lexical decision condition was given as a filling condition in the administration order of the conditions without making the subjects suspicious

TABLE 13

The design of experiment 4

GROUPS		CONDITIONS
1	BOURDON	1
	POSNER NAME	2
	LEXICAL DECISION	3
	LEX-DEC + NAME (1)	4
	BOURDON + NAME (1)	5
	BOURDON + LEX-DEC	6
	BOURDON + NAME (2)	7
	LEX-DEC + NAME (2)	8
2	BOURDON	1
	POSNER PHYSICAL	2
	LEXICAL DECISION	3
	BOURDON + PHYSICAL (1)	4
	LEX-DEC + PHYSICAL (1)	5
	BOURDON + LEX-DEC	6
	LEX-DEC + PHYSICAL (2)	7
	BOURDON + PHYSICAL (2)	8

NOTE. Condition 1 through 3, and 4 through 8 were balanced across subjects (per group)

with regard to purpose of the experiment.

5.6.2 Results

Preview. First, the overall average RT curves of the homogeneous conditions and the mixed conditions are again in line with the inhibition hypothesis. This means that on the average the RT curves of the homogeneous conditions are more increasing than the RT curves of the mixed conditions. This difference in the shape of the time series is again illustrated by the number of increasing and decreasing individual time series. Table 7 shows that the homogeneous conditions also have the larger number of increasing RT curves in experiment 4.

Just as was reported for experiment 2 and experiment 3, the error rate and the RT variance increase from the first to the latter four segments. The mean RT variance for the first segment is 0.33 and the average of the latter four segments is 0.38, $F(1,84)=15.24$, $p<.001$. The corresponding figures for the mean error rates are 0.7 against 1.1, $F(1,84)=17.07$, $p<.001$. However, no interaction between this contrast and the conditions was found neither for the RT variance, nor for the error rate.

Homogeneous versus Mixed. This section contains ANOVAs concerning the comparison of the homogeneous versus the mixed conditions for the total group of subjects. The next section deals with the ANOVAs per group, in which only the relevant mixed conditions are involved.

TABLE 14

Means and F-values of RT variables in experiment 4 (first presentation of mixed, see design)

VARIABLES	Conditions		F	Sign. of F
	Homog.	MIXED	(df=1,70)	
RT_{Mean}	3.54	3.38	14.91	p <.001
$RT_{Minimum}$	2.78	2.76	0.19	p >.05
$RT_{Variance}$	0.23	0.15	16.02	p <.001
Error Rate	5.31	5.41	0.03	p >.05
DT/PT	0.28	0.22	14.18	p <.001

Homog.= Average across Bourdon, Posner, and Lexical-Decision (N=16, per task)

MIXED = Average across all three MIXED2 task combinations (N=16)

Table 14 shows the results of the ANOVAs comparing homogeneous with mixed Completely in line with the inhibition hypothesis, the mixed conditions have significantly lower values on DT/PT, on the $RT_{Variance}$, and on the RT_{Mean}, and no differences are found on the $RT_{Minimum}$ or the error rate. These ANOVA results are even more clear-cut than those of the first two experiments, since in this case the processing time (estimated by the $RT_{Minimum}$) appears equal for both conditions The differences found on DT/PT, the $RT_{Variance}$, and on the RT_{Mean} constitute clear evidence for the inhibition theory.

Same tasks mixed versus different tasks mixed. Figure 13 shows the curves of the Physical match/Bourdon condition versus the Physical match/Lexical decision condition for group 2 The differences in the slopes of the fitted RT curves supported only very slightly the predictions The first combination of which it was assumed that the overlap of processors would be larger, indeed had the more increasing averaged RT curve

In the other group (group 1), however, the results were contradictory to the predictions The Name match/Bourdon combination had a more increasing curve than the Name match/Lexical decision combination (see figure 14) It was assumed that the Name match and the Lexical decision task would have more processors in common, and therefore would show a larger inhibition effect, i.e. a more increasing curve

These results are clearly illustrated by the number of increasing individual RT curves in each condition as shown in table 15. The Name match/Bourdon combination has more increasing curves in group 1, and the Physical match/Bourdon combination has one increasing curve more in group 2 It was predicted, though, that group 1 would have far more increasing curves in the Name match/Lexical decision condition and that group 2 would have far more increasing curves in the Physical match/Bourdon condition.

The ANOVAs (table 16) show no difference on DT/PT between the mixed conditions in either group Table 16 also shows no difference of the mean values of DT/PT between the mixed conditions per group The conditions differ only markedly on the RT_{Mean}, but this difference can be ascribed to the higher difficulty of the Lexical decision task

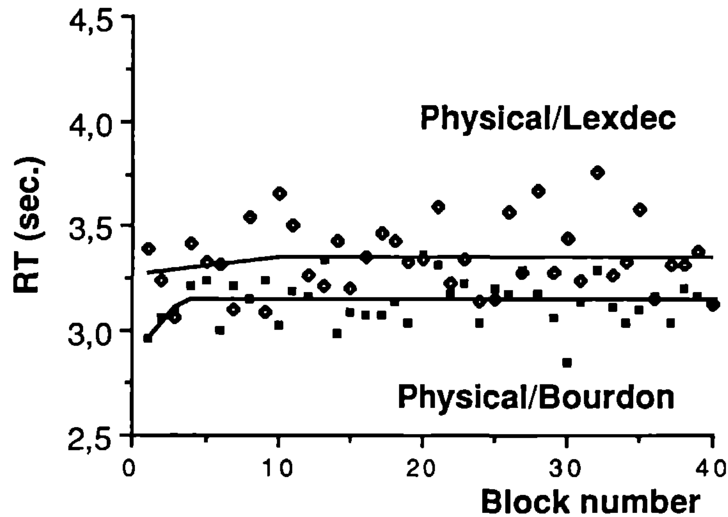


FIGURE 13

The RT curves of the Bourdon/Physical match condition and the Lexical-decision/Physical match condition

5.6.3 Discussion

Assuming that the Physical match task acts upon the same processors as the Bourdon task, and that on the other hand the Name match task uses the same processors as the Lexical decision task, the inhibition theory predicts that for each group separately the mixed conditions with the more similar tasks would yield more increasing RT curves, i.e. more DT, than the mixed conditions with the less similar

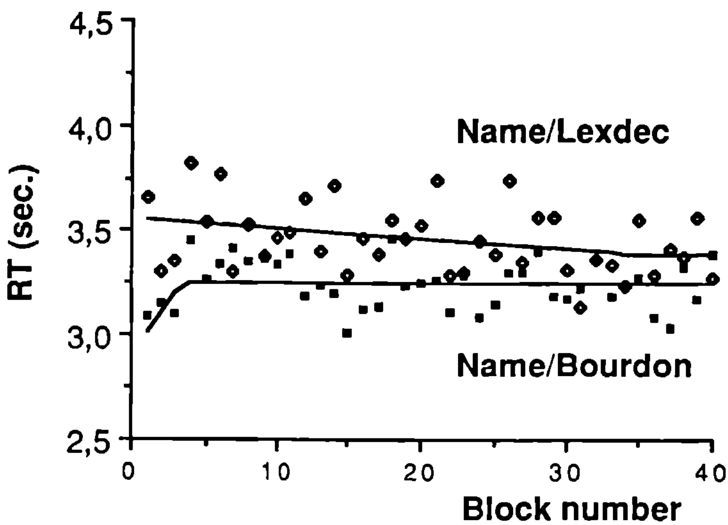


FIGURE 14

The RT curves of the Bourdon/Name match condition and the Lexical-decision/Name match condition

tasks. The results did not support the predictions. The reasons for these negative findings can be either that the theory does not hold, or that the chosen tasks do not use the same processors.

The discussion needs some refinement on this point. Besides the overlap of processors there are at least two other factors that influence the inhibition mechanism, (1) the time needed by the processors to recover, and (2) the processing time of the alternative task. To start with the last factor, it is evident that the processor of the task with the shorter processing time has more time to recover than the processor of

TABLE 15

Number of increasing and decreasing individual time series per condition per group

GROUP	CONDITION	INCREASING	DECREASING
1	NAME/BOURDON (N=8, 2 sessions)	8 (2)	8 (0)
	NAME/LEX-DEC (N=8, 2 sessions)	5 (0)	11 (4)
2	PHYSIC/BOURDON (N=8, 2 sessions)	9 (0)	7 (0)
	PHYSIC/LEX-DEC (N=8, 2 sessions)	10 (0)	6 (2)

Note. Between brackets: number of significantly increasing or decreasing curves (α=.05)

the other task. If, however, the response time of the shorter task, is long enough, the processor of the task with the larger processing time also has enough time to recover sufficiently. (In this reasoning we assumed that the processors of the two tasks do not overlap.)

These notions should be given more consideration in future research on mixed tasks with overlapping processors. Regarding Experiment 4 the first conclusion to be drawn is that the tasks did not have that much processors in common, as we supposed they would have. Further, the Lexical decision task had the highest PT (3.8 seconds over a block of six trials), but this PT was not that much larger than the PTs of the other tasks (3.5 seconds for the Name match, 3.2 seconds for the Physical match, and 3.5 seconds for the Bourdon). No convincing evidence was found that the Lexical decision trials cut out of the mixed conditions show a more increasing RT curve than the RT curves of the trials of the other tasks.

Given the earlier results the inhibition theory is not abandoned at this moment. Instead the conclusion is drawn that apparently the human information processing

TABLE 16

Means and F-values of the mixed conditions per group

VARIABLES	Conditions BOU/POS	POS/LEX	F (1,21)	Sign. of F
GROUP 1 (Name match)				
RT_{Mean}	3.25	3.46	12.23	$p < .001$
$RT_{Minimum}$	2.69	2.79	4.20	$p > .05$
$RT_{Variance}$	0.13	0.16	1.75	$p > .05$
Error Rate	4.9	5.8	0.92	$p > .05$
DT/PT	0.21	0.24	2.19	$p > .05$
GROUP 2 (Physical match)				
RT_{Mean}	3.14	3.35	17.58	$p < .001$
$RT_{Minimum}$	2.61	2.72	3.97	$p > .05$
$RT_{Variance}$	0.11	0.18	8.42	$p < .01$
Error Rate	4.9	4.7	0.50	$p > .05$
DT/PT	0.20	0.23	2.63	$p > .05$

Note. Both sessions are considered in these analyses.

system may be organized in a different way from what we assumed and that the tasks used in experiment 4 each have their own specific processors. A replication of this last experiment should be conducted with tasks, of which it is much more likely that they use the same processors. For example, the Physical match task can be administered either with alphabetic characters or mathematical symbols. Mixing these two tasks would render a task that could be seen as a homogeneous task. Therefore, about as many increasing RT curves should be found in this mixed condition as in the two corresponding homogeneous task conditions.

In the next chapter a second attempt is reported which examines whether it is possible to discriminate between tasks having few processors in common and tasks sharing many processors. The discriminating factor should be the amount of distraction time elicited by the alternation of two tasks. This second attempt yielded more promising results.

5.7 Concluding remarks

The aim of this chapter was to give an adequate explanation for the consistently found decrement in continuous RT performance. The inhibition theory explains why RT performance gets worse. The main feature of this theory is the inhibition mechanism, which says that a continuous activated processor gets inhibited ('blocked') and consequently needs a recovery period. In some former studies the massed versus spaced experiments already demonstrated the explanatory value of the inhibition theory (chapter 4, see also Van Breukelen et al., 1987b). The present study added empirical support, since the predicted homogeneous versus mixed condition effect was found. The cognitive model depicted in figure 1 (chapter 3) and figure 12 might be a helpful illustration in the development of theories in this field of attention and performance. For example, the inhibition mechanism seems a good candidate for explaining the decrement of RT performance in vigilance tasks, despite the work of Parasuraman (1985).

The distinction between underload and overload to characterize a specific task situation as given by Welford (1965) and others is of minor importance to the inhibition theory. The inhibition mechanism is thought to be present in every task situation, but it can be of less influence in some task situations, e.g. in tasks with (a large) processing time variability. For the domain of homogeneous tasks the inhibition mechanism is responsible for the decrement in performance according to the theory presented in this study.

A challenging direction in extending the inhibition theory is the mathematical modeling of the mixed task performance. The activation of the non-overlapping processors of the second task is releaving the first task, whereas the activation of the overlapping processors inhibits by definition the processors of the first task. Pulling the line a bit further along this way of thinking the mixed task condition may prove a fruitful instrument in determining how much two tasks have in common i.e. how many processors the two tasks share. The next chapter explicitly deals with what could be called the discovery of mental processors.

6 DISCOVERING MENTAL PROCESSORS: EXPERIMENT 5

A second attempt is reported of discovering mental processors in a mixed more versus mixed less paradigm. Three tasks were pairwise alternated: identifying three, four, or five dots; distinguishing among the words 'three', 'four', and 'five'; distinguishing among the digits '3', '4', and '5'. It turned out that words and digits call upon the same mental processors, because the alternation of these two tasks showed a performance decrement comparable to administering the tasks separately. Both mixing words and dots, and mixing dots and digits resulted in the usual mixed versus homogeneous data implying that the tasks in those combinations make use of different mental processors.

6.1 Introduction

In the last experiment of the previous chapter a first attempt was made to find evidence in favor of the logical consequence of the inhibition mechanism in a mixed task condition, namely that mixed tasks performance is better or worse to the degree that the tasks involved call upon the same mental processors (see figure 12 of chapter 5). The results of that particular experiment were disappointing in as far as virtually no evidence was found supporting the idea that different tasks make more or less use of the same mental processors.

In this chapter a second attempt will be reported. This time an experiment was done containing tasks that have a high resemblance at first sight. The decision process was the same for each task: answer YES if it is a four, answer NO if it is either a three or a five. The following three tasks were administered: (1) identify how many dots are displayed, (2) distinguish among the words 'three', 'four', and 'five', and (3) distinguish among the digits '3', '4', and '5'. The tasks were given separately and in combinations of two, which implies that a total of six conditions was given to each subject.

The expected effects fall into two categories. First of all, a homogeneous versus mixed tasks effects was expected. Therefore, the same predictions are tested as given in chapter 5:

(1) RT curves in a homogeneous condition will be more increasing than in mixed

conditions,

(2) the RT variance in a homogeneous condition will be more increasing than in a mixed condition,

(3) distraction time will be larger in a homogeneous condition than in a mixed condition,

(4) RT_{Mean} will be larger in homogeneous conditions than in mixed conditions, and

(5) $RT_{Variance}$ will be larger in homogeneous conditions than in mixed conditions.

Secondly, some exploratory tests are performed to discover whether the three tasks call upon the same mental processors. So, for each alternating task condition the comparison between homogeneous and mixed is investigated in detail.

6.2 Method

Subjects. Sixteen female and two male students volunteered in this experiment. Each of them got the same six experimental conditions which took them about two hours to complete.

Task and procedure. Three different two choice RT tasks were used in this experiment: (1) the Bourdon task as described in chapter 4 and Chapter 5, (2) a digit identification task with stimuli '3','4', and '5', and (3) a word identification task with stimuli 'three', 'four', and 'five' (presented in dutch). For each of the three tasks the instruction was to answer YES in case four dots, '4', or 'four' were shown, and otherwise to answer NO. As in all of the earlier reported experiments, subjects were instructed to work fast, but to commit no errors.

Design. The experimental conditions were made up of three homogeneous conditions, which implied the administration of a single task with massed trials, and three mixed conditions, which meant the administration of two quasi-randomly alternated tasks also with massed trials. All subjects started with six practice series of 120 trials, one of each condition. Each experimental condition contained a total of 240 trials and was preceded by another practice series of 120 trials. The sequence order of the experimental conditions was balanced over subjects.

6.3 Results

Homogeneous versus Mixed. As was explained in detail in chapter 5, it is predicted that the trend in RT and in the residual RT variance is more increasing in the homogeneous than in the mixed condition. Further, the ratio of PT over DT should be larger in the mixed condition and $RT_{Variance}$ should be larger in the homogeneous condition.

Table 17 shows for each condition the number of increasing and decreasing RT curves. Overall, 45 of the 54 RT curves of the homogeneous conditions were increasing, whereas only 34 of the 54 RT curves of the mixed condition were increasing

TABLE 17
Number of increasing and decreasing individual time series per condition (N=18)

CONDITION	INCREASING	DECREASING
Bourdon	15 (4)	3 (0)
Digit identification	14 (9)	4 (1)
Word identification	16 (9)	2 (0)
Bourdon/Digits	9 (2)	9 (1)
Bourdon/Words	12 (2)	6 (1)
Digits/Words	13 (2)	5 (2)

Note. Between brackets: number of significantly increasing or decreasing curves (α=.05).

The residual RT variance turned out to increase significantly more in the homogeneous conditions, $F(1,102)=5.75$, $p<.05$. The interaction tested was the difference in the increase of the residual RT variance from the first 8 blocks of trials to the remainder of the trial series between the homogeneous and the mixed conditions. The residual RT variances were 0.25 for the first 8 blocks of trials and 0.34 for the remainder in case of the homogeneous conditions, whereas the figures for the mixed conditions were 0.27 and 0.29.

The ratio PT/DT, which is a measure for concentration as will be explained in chapter 8, was significantly larger in the mixed conditions; the means were 4.45 for the homogeneous conditions and 5.32 for the mixed conditions, $F(1,85)=11.34$, $p<.001$. In table 18 the means for PT/DT are shown in case of the specific comparisons of homogeneous and mixed for each mixed condition. In all cases PT/DT turned out to be larger in the mixed condition. However, some clear distinction exists in the magnitudes of these differences. In the next three sections the mixed conditions will be discussed in more detail.

Bourdon and Digit identification. $RT_{Minimum}$, the processing time, is significantly lower in the homogeneous condition than in the mixed condition. This is in agreement with the idea that alternating two tasks requires some extra processing capacity, especially if the two task employ different processors. From the Working Memory (Baddeley, 1986) point of view, the alternation of two different tasks necessitates that different mental processors have to be kept active in working memory, which evidently takes extra time in comparison to the execution of only a single task.

PT/DT is significantly higher in the mixed condition. This result confirms the prediction that performance gains from alternating two tasks, i.e. that the inhibition of one task is reduced due to the time devoted to another task.

In terms of the mixed inhibition model these results imply that the Bourdon task and the Digit identification task activate different processors.

Bourdon and Word identification. The results of the comparison of the mixed Bourdon-Word identification condition with the corresponding homogeneous conditions were very similar to those of the Bourdon-Digit identification condition, as is shown in table 18. One exception is the absence of a difference with respect to RT_{Mean}. The increase in RTs in the homogeneous conditions is that large that the (initial) difference found on $RT_{Minimum}$ has disappeared in the between conditions effect on RT_{Mean}. In other words the differences in processing time are balanced by the differences in distraction time.

The conclusion in this case is also that the Bourdon task and the Word identification task apparently make use of different processors.

Digit and Word identification. No significant differences are found between the mixed and homogeneous conditions of the Digit identification and the Word identification task. The directions of the differences are, however, in agreement with the

TABLE 18

Means and F-values per mixed condition

VARIABLES	Conditions: Homogeneous	Mixed	F (1,34)	Sign. of F
Bourdon - Digits				
RT_{Mean}	2.79	2.93	10.59	$p < .01$
$\hat{C}$	4.50	5.41	9.15	$p < .01$
$RT_{Minimum}$	2.24	2.44	28.34	$p < .001$
$RT_{Variance}$	0.19	0.12	1.22	$p > .05$
Error Rate	6.4	6.7	0.17	$p > .05$
Bourdon - Words				
RT_{Mean}	3.01	3.05	0.57	$p > .05$
$\hat{C}$	4.53	5.65	10.38	$p < .01$
$RT_{Minimum}$	2.43	2.55	11.00	$p < .01$
$RT_{Variance}$	0.17	0.13	1.46	$p > .05$
Error Rate	6.84	5.5	3.75	$p > .05$
Digits - Words				
RT_{Mean}	2.74	2.78	1.04	$p > .05$
$\hat{C}$	4.32	4.90	1.93	$p > .05$
$RT_{Minimum}$	2.18	2.25	2.76	$p > .05$
$RT_{Variance}$	0.19	0.10	1.88	$p > .05$
Error Rate	5.64	6.06	0.28	$p > .05$

Note. 'Homogeneous' implies the average of the two corresponding homogeneous conditions.

predictions regarding the homogeneous versus mixed condition effect.

These results fit exceptionally well into the picture of two alternated tasks making use of a large proportion of the same processors, as was outlined in the description of the mixed inhibition model. Putting it the other way around, we get that, if two tasks share many processors (i.e. P in equation [34] is relatively large), it is predicted that the differences between the homogeneous and the mixed conditions will vanish. This is exactly what is found in this comparison. It can, further, be pointed out that also the difference in $RT_{Minimum}$, the processing time, is expected to disappear, since the large number of shared processor consume the same amount of processing capacity in the mixed condition as the processors of the homogeneous conditions. What is meant, is that the mixed condition gradually becomes a homogeneous condition depending on the proportion of processors that is shared.

The conclusion in this last case, then, is that the Digit identification task and the Word identification task activate to a considerable extent the same processors. It seems intuitively very reasonable that digit identification and word identification share a *semantic* identification processor, which is distinct from a *figural* identification processor used in the Bourdon task.

6.4 Discussion

More evidence is supplied for the existence of a homogeneous versus mixed effect on simple mental tasks as predicted by the inhibition theory. The RTs as well as the residual RT variances are more increasing in case of the homogeneous conditions. Therefore, also in case of the contrasts of the separate mixed conditions with their corresponding homogeneous conditions, the predicted homogeneous versus mixed effects were consistently in the expected direction.

However, this time we found that some differentiation existed in the magnitudes of the difference between homogeneous and mixed. The data suggest that the Digit identification task and the Word identification task share a significant set of processors, whereas the Bourdon task seems to employ mainly different processors than the other two tasks. Interpreting these results, we reach the conclusion that a semantic processor might be most important, if we have to distinguish among words or among digits, whereas most probably a figural identification processor is active in the Bourdon task.

Assuming that these conclusions are in the right direction, the more general conclusion of this experiment, then, is that a mixed task paradigm might give a lead to the discovery of mental processors. The inhibition theory predicts that if a mental processor is emloyed continuously it will become inhibited. Using the reverse logic, we state that if a mental processor gets inhibited during continuous performance, it is employed continuously. And the processor can only be employed continuously, if the two tasks in the mixed condition make use of the same mental processor. Giving credit to this line of reasoning implies that a mixed tasks paradigm indeed serves the discovery of mental processors.

7 THE CONCEPT OF MENTAL SPEED: A SHORT NOTE

This chapter contains a few notes on the concept of mental speed. Further, it is shown how mathematical models can be used to predict individual differences. This chapter serves as an introduction to the measurement of individual differences by means of the mathematical model approach.

7.1 Introduction

The concept of mental speed is mostly encountered within theories of intelligence. Unfortunately, there is an overwhelming amount of theories on intelligence (see Sternberg, 1982, 1985). Robert Sternberg (1985) distinguishes two broad classes of theories of intelligence: the differential or psychometric theories of intelligence and the cognitive or information processing theories of intelligence.

The psychometric theories have in common their attempt to understand intelligence in terms of a set of underlying abilities, such as verbal ability or reasoning ability. Factor analysis is the most commonly employed technique to reveal these abilities. The primary difference between the theories, then, are (1) the number of factors, and (2) the geometric arrangement of these factors. For instance, Spearman (1927) proposed that intelligence comprises mainly a general factor and further some specific factors, whereas Guilford (1967) claims the existence of 120 distinct factors. Most of these theories contain one or more speed factors, such as the perceptual speed factor in Thurstone's primary mental abilities (Thurstone, 1938).

The cognitive theories of intelligence have in common their attempts to understand human intelligence in terms of mental processes that contribute to cognitive task performance. Some investigators have proposed to understand intelligence in terms of sheer speed of information processing devising very simple tasks in order to measure pure speed uncontaminated by other variables. Others studied very complex forms of problem solving de-emphasizing the role of speed in mental processing. Sternberg (1985) illuminates four forms of mental speed, namely pure speed, choice speed, speed of lexical access and speed of reasoning. He argues that the more complex the task the more informative speed is as a measure of intelligence. For instance, speed of processing in an analogical reasoning task would tell more about intelligence than the speed of crossing out *a*'s in a cancellation task.

7.2 Mental Speed and Intelligence

The present point of view, however, is more in line with the theoretical view of Jensen (1982) who states that especially the reaction time (RT) in simple mental tasks is related to intelligence. More specifically, he states that there exists an increase in the absolute value of the correlation between RT (measured per task unit) and IQ until RT reaches a value of about 1 second. When the processing time is greater than that, further increases in task complexity do not result in a further increase in the RT-IQ correlation. To put this in another way, the correlation between RT and ability measured by the number of items correct on a typical intelligence test usually breaks down completely (Jensen, 1982, p.110). For example, the correlation between the solution times for Raven Matrices items and total score on the Raven has been found near zero in three studies (Jensen, 1979, Snow et al., 1976, White, 1973).

Jensen (1982), further, sketches a theory of the relation of RT and intelligence in a way which comes close to the ideas of the present author, as expressed in chapter 7. Although this theory may be rather speculative, it seems worthwhile to cite Jensen here serving the purpose of framing the context of how RT on simple mental tasks could be linked to such a complex concept as intelligence. Jensen (1982, p.122) proposes the following lines of thought:

> *Speediness of mental operations is advantageous in that more operations per unity of time can be executed without overloading the system. Secondly, there is rapid decay of stimulus traces and information, so that there is an advantage to speediness of any operations that must be performed on the information while it is still available. Thirdly, to compensate for limited capacity and rapid decay of incoming information, the individual resorts to rehearsal and storage of the information into intermediate or long-term memory (LTM), which has relatively unlimited capacity. But the process of storing information in LTM itself takes time and therefore uses up channel capacity, so there is a "trade-off" between the storage and the processing of incoming information. The*

> *more complex the information and the operations required on it, the more time that is required, and consequently the greater the advantage of speediness in all the elemental processes involved. Loss of information due to overload interference and decay of traces that were inadequately encoded or rehearsed for storage or retrieval from LTM results in "breakdown" and failure to grasp all the essential relationships among the elements of a complex problem needed for its solution. Speediness of information processing, therefore, should be increasingly related to success in dealing with cognitive tasks to the extent that their information load strains the individual's limited channel capacity. The most discriminating test items thus would be those that "threaten" the information processing system at the threshold of "breakdown". In a series of items of graded complexity, this "breakdown" would occur at different points for various individuals. If individual differences in the speed of the elemental components of information processing could be measured in tasks that are so simple as to rule out "breakdown" failure, [...] it should be possible to predict the individual differences in the point of "breakdown" in the more complex tasks. I believe this is the basis for the observed correlations between RT variables and scores on complex g-loaded tests.*

Berger (1982) elaborates the relation between mental speed and intelligence on a more general level. He starts by stating that in most research on intelligence the concept of mental speed has been underdeveloped and that mental speed has been treated as a 'mini black box' slotted into a broader framework. The spin-off for a conceptual digression of mental speed is the assumption that the observed RT contains more than just the time to solve the item. As was already mentioned in chapter 1, Peak and Boring (1926) were among the first who hypothesized that the RT contains processing time to solve the item and distraction time spent on other activities. The processing time can be further dissected into encoding time, decision time, response selection time, and response execution time. In fact, as Berger (1982) indicates, the decomposition of RT can be made in even more basic elements. He rightly emphasizes the fact that it is the RT for a single item that is decomposed, and that even at this level there are a number of complications in conceptualizing mental speed.

For the present purpose it seems not necessary to divide the processing time in its elementary components. The RT is decomposed in just two major parts, processing time and distraction time. Processing time contains all the time consumed by the mental processes involved in the solution of the task at hand. Distraction time, on the other hand, is the time wasted on mental activities not immediately related to the progress in solving the task. Hence, mental speed is regarded as the amount of mental work done per unit of processing time.

7.3 Mathematical models for speed

The Thurstone model

A first attempt of incorporating mental speed within a model aiming at the measurement of intelligence was given by Thurstone (1937). For each individual subject a three dimensional space could be set up, in which the axes represent the difficulty of the items, the probability of giving a correct answer, and the response time for giving an answer. Thurstone, then, defined mental ability (or intelligence if you wish) of a subject as the difficulty (of an item) at which the probability is 0.5 that the subject will give a correct answer in infinite time. This model of Thurstone is mainly of theoretical importance, as it is experimentally almost impossible to devise such a large number of items to be able to draw for each individual subject an empirical space of item difficulty, precision, and mental speed.

A framework for models of speed and precision

Roskam (1987) gave a more complete picture of all the theoretical components involved in intelligence test performance. Besides precision, item difficulty, and mental speed he distinguishes accuracy, resources, concentration, and persistence. To indicate in which direction the development of such a psychometric theory of intelligence moves, the following global function for precision, ξ, was given by Roskam (1987, p.168). In this case the precision is the probability of a correct response for an item of fixed difficulty.

$$\xi_{vi}(t) = f(\alpha_v, \kappa_v, \tau_{vi}(t), \lambda_v),$$

$$\begin{aligned} \textit{where } \alpha &= \textit{accuracy}, \\ \kappa &= \textit{resources, knowledge etc.}, \\ \tau &= \textit{elapsed invested processing time}, \\ \lambda &= \textit{mental speed}, \\ i &= \textit{item, and} \\ v &= \textit{subject}. \end{aligned} \qquad [28]$$

This function can be read as follows. The probability of a correct response at time t for a given subject and item is a function of the subject's accuracy, knowledge, and mental speed, and of the invested processing time up till time t. Parameter τ_{vi} implies the efficiency of processing of a subject on a certain item. The inhibition theory plays of course an important role in determining the function $\tau_{vi}(t)$.

Roskam continues by outlining some specific models and their consequences, but that goes beyond the scope of the present study. We will restrict ourselves to models dealing with response times (see Van Breukelen, 1989b, pp.117-157). The basic idea of these models is that the time to give a (correct) answer increases with item difficulty and decreases with a subject's mental speed.

It should be stressed that τ is the elapsed invested *processing* time. If a test is administered in such a way that there remains no time to rest, and if the items of the test are also of the same kind, then we will state that the observed RT will contain both processing time and distraction time. Roskam also incorporated a parameter of concentration: η. If concentration is considered, i.e. if distraction time is considered, then τ will be smaller than t. Roskam proposed to use $\tau = \eta t$ with $0 < \eta \leq 1$ (see Roskam, 1987).

A special class of models that contain a concentration or distraction parameter are the processing-distraction models. These models do not take precision or item difficulty into consideration. This means that these models require that the items are of the same difficulty and that the subjects work at a constant speed-accuracy trade-off. These models are meant to measure processing time and distraction time, or mental speed and concentration.

Some processing-distraction models for speed

In the processing-distraction models the processing time given a subject's mental speed, an item's difficulty, and the level of accuracy is supposed to be constant. This constant processing time is denoted by parameter A. This constancy of processing time assumption is only plausible if the items are of the same difficulty, if the subjects work at a constant speed-accuracy level, and if the task is overlearned. These requirements can only be fulfilled if the items are very simple.

Still, the RTs will also vary in the processing-distraction models, if we assume that $\tau < t$. However, in this case the fluctuation is solely due to the fluctuation in the distraction times. The RT for a single item is thought to be built up of a series of alternating processing and distraction periods. The processing periods sum up to a constant A. These models were described in chapter 3.

7.4 Concluding remarks

This short chapter was meant as an introduction of using the processing-distraction models in case of the measurement of individual differences in mental speed. Given the ideal situation in which the INHIBITION model parameters are available for each individual, parameter A would give an impression of the individual differences in mental speed. From Jensen's point of view, these differences would be connected to differences in intelligence.

It stands, however, beyond any doubt that a subject's performance on an intelligence test is a function of his mental speed, his accuracy, his knowledge, his persistence, his desired level of precision, his concentration, and the difficulty of the items of the test. Starting from this framework of Roskam (1987) it is worth the effort to obtain estimates of the parameters that determine a subject's performance. This road of investigation may ultimately lead to an answer to the question if mental speed makes up the main source of individual differences in intelligent behavior, as is more or less maintained by Jensen (1982).

In the next chapter we will investigate another source of individual differences which also concerns intelligènce test performance, namely *concentration*.

8 ON THE MEASUREMENT OF CONCENTRATION

Concentration tests are often used in professional settings. Still, concentration is an ill-defined concept. Within the inhibition theory concentration is defined as the ratio of effective processing time to ineffective processing time. This last term is also called distraction. In this chapter a series of experiments is presented in which effects on distraction and concentration are tested. Further, the concentration measure is correlated over tasks to get an idea of its stability, and correlations between concentration and other test materials are gathered to find out if it is reasonable to suppose that what is usually called concentration is measured. On the whole it turned out that if certain conditions are fulfilled this measure is able to predict difficulties in concentration quite well.

8.1 Part I: the theory

By common understanding concentration implies an ability and attitude to keep up a certain level of good performance over some period of time. A low concentration is indicated by a large variance in the speed of performance, by loosing speed and by an increasing error rate. This concept of concentration is frequently encountered in the literature on psychological tests. This concept is also labeled as sustained attention or vigilance within the field of experimental psychology. As concentration points to individual differences this term suits the present purposes best.

Concentration or attention belong to the earliest issues in the field of psychodiagnostics. On the one hand there was an interest in the ability to concentrate by child psychologists, on the other hand psychiatrists were in search of ways to measure fluctuations in attention. For instance, Godefroy (1915) tried to discriminate patients with epileptic disorders from normal patients by inspecting the fluctuations in RTs on the Bourdon-Wiersma test. He realized that the fluctuations in RTs told more about attentional disorders than merely the mean RT.

Some years earlier Kraepelin and his co-workers (Oehrn, 1895; Kraepelin, 1902; Hylan & Kraepelin, 1904) started to investigate individual differences of performance fluctuations with time on task. Their subjects had to add digits two by two in an almost endless row. The test designed by Kraepelin (1902) lasted at least one hour. Every 3 minutes the number of correct additions was registered. In this way a so-called working curve ('Die Arbeitskurve') was obtained for each subject.

Pauli (1938) and later Arnold (1975) standardized this test, which became known as the Pauli-test. Other tests specifically designed to test concentration, are the Konzentrations-Verlaufs-Test (Abels, 1954), the Bourdon test (see, Godefroy, 1915; or Vos, 1988), the Grünbaum test (Van der Horst, 1939) and the Attention Diagnostic Method (Rutten, 1964). These latter three tests are commonly used in all kinds of clinical settings in the Netherlands (see De Zeeuw, 1976). Although scoring manuals are available to guide a psychologist or psychiatrist in obtaining conclusions on a patient's concentration or his fluctuation in attention, a theory underneath these guidelines completely lacks.

The first aim of this chapter will be to show how concentration can be defined within the inhibition theory. It turns out that from the mathematical formalization of this theory a measure for concentration can quite easily be derived. The second aim is to propose a standard procedure for concentration testing. This procedure takes account of task construction, administration, and analysis. Further, some first results are shown regarding the validity of this concentration measure.

8.1.1 A measure of concentration

Concentration tests can be administered in two different pencil-and-paper versions: (1) the number of items finished within a fixed time-interval is consecutively recorded, or (2) time is registered for a fixed number of items. Administration per computer evidently has the great advantage of registering a RT on every trial. From these data the mean RT (RT_{Mean}), the variance of the RTs, ($RT_{Variance}$), and also the range of the RTs can be calculated. Furher, some measure for precision is derived from the data, e.g. the error rate. These variables, then, are used to discriminate between children with concentration problems and normal children, or to discriminate between patients with attentional disorders and patients with normal attentional achievements. However, no theory is yet available to tell what variable would discriminate best between those groups. Moreover, it can be shown that all the variables mentioned are disputable regarding the measurement of concentration (see Van Breukelen & Souren, 1990).

Chapter 3 provides a detailed outline of the inhibition theory. The essential assumption of the inhibition theory is that a RT contains besides processing time which is time needed to solve the task, also distraction time which is time spent on irrelevant mental activities. A second assumption which makes the theory more restrictive, is that an inhibition mechanism determines the amount of distraction time. How this inhibition mechanism works was described in chapter 3.

Concentration can be defined in a number of different ways, e.g. it can be defined as the inverse of the distraction time (DT), or as the ratio of DT and the total RT. We desire, though, a measure that expresses the efficiency of processing. A high level of concentration implies a very efficient way of processing the task at hand. Therefore, we propose to use the effective processing time (PT) per unit of the ineffective processing time, which is DT, as a measure for concentration.

This measure for concentration can be obtained easily, if we take only the first two assumptions of the INHIBITION model (or of the IMAX model) into considerations. From the assumption that a RT is the sum of processing time and distraction time, together with the assumption that the processing time is constant per trial, it immediately follows that all variability is due to distraction time. Hence, the mean DT per trial should be equal to RT_{Mean} minus A, the processing time. Defining the measure for concentration as the ratio of PT and DT leads straight forward to equation [29].

$$\hat{C} = \frac{A}{(RT_{Mean} - A)} \qquad [29]$$

In most experimental situations it appears that decreasing RT curves do occur despite the practice series that were administered. In those cases the estimate of A (as estimated by [26] of chapter 3) will be larger than RT_{Mean} and, consequently, a negative value would be the estimate for the amount of distraction time, which is unreasonable. In order not to be forced to leave cases with a decreasing RT curve out of the analyses, a more robust estimator is necessary for the processing time. Van Breukelen (1989a) showed that $RT_{Minimum}$ is such a robust estimator, although slightly biased. Taking $RT_{Minimum}$ as the estimator for A, $\hat{C}$ is approximated by:

$$\hat{C} = \frac{RT_{Minimum}}{(RT_{Mean} - RT_{Minimum})} \qquad [30]$$

From a mathematical point of view equation [29] is not nicely derivable from the IMAX model (nor from the INHIBITION model). In preciser words, the ratio given in [29] is not an unbiased estimator of PT/DT. It is, however, possible to derive the unbiased estimator for DT/PT, which is

$$E(DT/PT) = \frac{RT_{Mean} - A}{A} \qquad [31]$$

Notwithstanding the possibility of using the estimator given in equation [31], we prefer to use $\hat{C}$ as our measure for concentration, because we consider it more important to offer a measure which is immediately interpretable as an indication of a high or a low concentration. $\hat{C}$ is a very robust measure for concentration and it indicates instantly the odds of effective and ineffective processing time. This measure will be used in the remainder of this chapter.

If it were possible to obtain unbiased and reliable estimates of the model parameters, other measures of concentration should also be considered. For instance, the stationary inhibition (given by $\delta\mu_1/\mu_2$) would be a very good candidate. This measure contains the equilibrium between the built up of inhibition and the breakdown of it. Ideally, the inverse of the stationary inhibition ($\mu_2/\delta\mu_1$) might be the most appropriate measure of concentration.

8.1.2 Factors improving concentration

Experimental factors that are able to improve the concentration, give in one way or the other the mental processors an opportunity to recover without impairing the performance on the task. Until now, we only know of two of such factors: rest periods and alternating tasks. Both factors were already mentioned and we will comment on them only briefly.

8.1.2.1 Rest periods (Spacing)

The inhibition theory states that mental processors need recovery periods. So, if recovery periods are experimentally supplied at regular intervals, performance is expected to be optimal.

In chapter 4 (see also Van Breukelen et al., 1987b) two experimental studies were reported in which a condition without rest periods (the massed condition) was compared with a condition with intermittent rest periods (the spaced condition). In the first experiment the Bourdon task served as the simple repetitive task, whereas a true/false digit-addition task was used in the second experiment.

It was predicted that the number of increasing RT curves (for each subject a RT curve can be fitted) would be larger in the massed condition than in the spaced condition. Furthermore, RT_{Mean} and $RT_{Variance}$ were expected to be higher in the massed condition. These predictions were supported by the data.

A reanalysis of these two studies with respect to the concentration measure $\hat{C}$ shows that $\hat{C}$ is significantly lower in the massed condition than in the spaced condition on both tasks. For the Bourdon task $\hat{C}$ was 4.52 for massed and 5.65 for spaced $F(1,117)=12.63$, $p<.001$, and for the Pauli task these figures were 3.82 against 5.91, $F(1,31)=24.72$, $p<.001$.

8.1.2.2 Alternating tasks (Mixing)

TABLE 19

$\hat{C}$ for the homogeneous and mixed conditions of the experiments of chapter 5 and chapter 6

Experiment	Homogeneous	Mixed	F	df	
2	3.23	3.77	7.46	(1,48)	p<.01
3	3.97	4.42	2.57	(1,44)	p>.05
4	4.01	4.74	11.57	(1,105)	p<.001
5	4.45	5.32	11.34	(1,85)	p<.001

In chapter 5 three experiments were reported in which a single task condition was contrasted with an alternating tasks condition. In this latter condition two or three different task were alternated. The idea was that the time devoted to executing the second task could be used by the processors of the first task to recover.

For example, in the first experiment the following three tasks were employed: the Bourdon task and the digit-addition task from the Van Breukelen and Jansen experiments (see chapter 4), and the Posner letter matching task (see Posner, 1978), were employed. These tasks were each administered in a separate condition, the so-called homogeneous conditions. Thereafter, the subjects got each combination of two tasks and the three task combination in the so-called mixed conditions. The trials of these latter conditions contained stimuli that were chosen randomly from the tasks. In this way a subject could get, for instance, a random order of dot patterns and digit-additions. Both tasks are two choice RT tasks, which implies that no confusion will arise in the response programming. It should be stressed that both the homogeneous and the mixed conditions are in fact massed conditions.

Assuming that the time spent on the second task serves as a rest period for the first task, the predictions for the homogeneous versus the mixed conditions are the same as those for massed versus spaced. So, the number of increasing RT curves, the RT_{Mean}, and the $RT_{Variance}$ were expected to be large in the homogeneous conditions. Although the results were not as evident as for the massed versus spaced experiments, the predictions were by and large supported by the data of all three experiments.

Also in this case we reanalyzed the data with respect to $\hat{C}$. Table 19 shows the results for $\hat{C}$ in the homogeneous and the mixed conditions. Except for the experiment 3, $\hat{C}$ is significantly larger in the mixed condition. In all three experiments the subjects processed the tasks most effective in the conditions where (at least) two tasks are alternated. The same conclusion can be reported for experiment 5 of chapter 6.

8.1.3 Spaced versus Mixed: Experiment 6

The conclusions of the experiments just mentioned seem to be that if someone wants to keep up a high level of concentration, either he has to rest at regular time intervals or he has to alternate the task at hand with some other task. The question remains which method is most effective.

In an experiment we explored the reduction in distraction time by administering the factors rest period and alternating task to the same subjects. Moreover, the experiment should prove again the beneficial effects of rest periods and mixing of tasks on concentration.

8.1.3.1 Method

Subjects. Nine female and seven male students participated to this experiment. Ages ranged from 18 to 35 of years with an average of 24. They all studied psychology.

Apparatus and Procedure. The Bourdon task, a digit-addition task (referred to as the Pauli task), and a lexical decision task served as the experimental tasks. All three tasks were rather simple two-choice RT tasks. In the Pauli task additions were shown which were either correct or incorrect. Of each addition the outcome was below ten. Stimuli of the lexical decision task were Dutch words. The subject had to decide whether it was a proper Dutch word or not.

Subjects were given a total of eight conditions divided into two sessions on two different days. A session consisted of first two massed conditions with a single task and then either two spaced conditions with a single task or two massed conditions with an alternation of two tasks. All conditions consisted of a practice series of 120 trials followed by an experimental series of 240 trials.

TABLE 20

The design of Experiment 6

SESSIONS	1	2
CONDITIONS	BOURDON massed	BOURDON massed
	PAULI massed	LEXDEC massed
	BOURDON spaced	BOURDON/LEXDEC
	PAULI spaced	BOURDON/PAULI

LEXDEC = the lexical decision task

NOTE. Sessions as well as conditions within sessions were counterbalanced over subjects except for the restriction that the massed conditions always came first.

The design matrix is shown in table 20. The Bourdon task and the Pauli task were administered in both the massed and the spaced version. The two mixed conditions were the alternations of Bourdon and Pauli on the one hand and of Bourdon and Lexical decision on the other. Sessions and conditions within sessions were as much as possible counterbalanced over subjects.

8.1.3.2 Results

For the homogeneous/massed conditions 46 increasing and 18 decreasing RT curves were found, whereas for the combined spaced and mixed conditions these figures were 38 increasing versus 26 decreasing. Also the average homogeneous/ massed curve is increasing explaining 56% of the variance if we fit the IMAX model to the data. More important, the residual variance of the homogeneous conditions is significantly increasing from the first 8 trial blocks to the remainder of the time series, $F(1,120)=8.04$, $p<.05$, and also the error rate increases, $F(1,120)=12.30$, $p<.001$. Although the average RT curves of both the spaced and the mixed conditions are slightly increasing explaining 8% and 15% of the variance respectively, neither the residual variance nor the error rate increased in these conditions. These results again confirm the inhibition theory.

In an overall ANOVA the homogeneous conditions were contrasted with the spaced and the mixed conditions together. RT_{Mean}, $RT_{Minimum}$, and $RT_{Variance}$ turned out to be higher in the homogeneous conditions, whereas the concentration measure was, as expected, lower in the homogeneous conditions (see table 21).

Spaced versus Mixed. The spaced conditions turned out to have a more reducing effect than the mixed conditions on all the task variables except for the effect on $\hat{C}$ (see table 22).

We need, however, to be more precise at inspecting this contrast of Spaced versus Mixed. The spaced conditions contained the Bourdon task in one case and the Pauli task in the other. The mixed conditions consisted of alternations of the Bourdon and Pauli tasks on the one hand, and of alternations of Bourdon and Lexical-decision on the other hand. So the conditions do not correspond exactly. However, as can be shown in the massed conditions of the Pauli task and the Lexical-decision task, the Pauli task always takes more time to be solved than the Lexical-decision task. For instance, RT_{Mean} of these two conditions were 4.19 sec. for the Pauli task and 3.45 sec. for the Lexical-decision task, $F(1,105)=100.10$, $p<.001$. This

TABLE 21

The ANOVAs for Homogeneous vs. Spaced and Mixed

Variables	Homog.	Spa/Mix	F	df	p
RT_{Mean}	3.62	3.35	33.65	1,105	<.001
C	4.38	4.76	4.41	1,105	<.05
$RT_{Variance}$	0.21	0.13	19.63	1,105	<.001
$RT_{Minimum}$	2.89	2.75	15.42	1,105	<.001
Error rate	8.95	8.17	1.90	1,105	>.05

TABLE 22

The ANOVAs for Spaced versus Mixed

Variables	Spaced	Mixed	F	df	p
RT_{Mean}	3.28	3.43	4.65	1,105	<.05
C	4.74	4.78	0.02	1,105	>.05
$RT_{Variance}$	0.11	0.15	2.60	1,105	>.05
$RT_{Minimum}$	2.69	2.80	4.64	1,105	<.05
Error rate	6.90	9.43	9.99	1,105	<.05

implies that the differences found between the spaced and mixed conditions on RT_{Mean} and $RT_{Minimum}$ hold a fortiori.

Contrasting Spaced Bourdon and Spaced Pauli with the mixed Bourdon Pauli condition yields $\hat{C}$=4.74 for the spaced conditions and $\hat{C}$=4.81 for the mixed condition, which indicates that the means are about equal.

Contrasting the spaced conditions with the corresponding massed conditions resulted in a significant difference on all the variables. This time the mean values for $\hat{C}$ were 4.74 and 4.23 for the spaced and massed conditions respectively, $F(1,45)=4.49$, $p<.05$.

TABLE 23

The first versus the second massed BOURDON

Variables	BOU1	BOU2	F	df	p
RT_{Mean}	3.32	2.98	13.29	1,105	<.001
C	4.30	4.73	1.42	1,105	>.05
$RT_{Variance}$	0.14	0.10	0.81	1,105	>.05
$RT_{Minimum}$	2.66	2.42	11.33	1,105	<.001
Error rate	7.06	7.50	0.15	1,105	>.05

BOU1= the first administration of massed BOURDON

BOU2= the second administration of massed BOURDON

The picture was less clear for the contrast of the homogeneous conditions and the two mixed conditions. The Bourdon/Pauli mix condition versus its corresponding homogeneous conditions yielded a significant smaller value for the mix condition on RT_{Mean}, $RT_{Variance}$, and $RT_{Minimum}$, and an almost significant larger value on $\hat{C}$. For the contrast of the Bourdon/Lexdec mix condition with its corresponding homogeneous conditions only $RT_{Variance}$ was significantly smaller in the mixed condition.

Finally, we contrasted the two Bourdon conditions. A very significant decrease of $RT_{Minimum}$ and RT_{Mean} was found. However, these two conditions did not differ on $RT_{Variance}$, $\hat{C}$ or the error rate (see table 23).

8.1.3.3 Discussion

The first conclusion to be drawn from this experiment is that it replicates in essence the findings of Van Breukelen and Jansen (Van Breukelen et al., 1987b) and Jansen and Roskam (1989): (1) the RT curves in the massed conditions are increasing accompanied by an increase in residual variance and error rate, (2) the spaced condition reduces distraction time, and (3) the mixed condition reduces distraction time.

This time, we also found a large effect of the spaced condition on the processing time, as estimated by $RT_{Minimum}$. Part of this effect could be due to learning, as the spaced conditions always followed the massed conditions. However, until now there is no evidence that learning is also the factor that could explain the effect on $\hat{C}$. For instance, the results of the first against the second session of the (massed) Bourdon task shows that learning can have a large effect on the processing time without changing the relative amount of distraction time.

Perhaps a bit surprising is the result that the mixed conditions and the spaced conditions do not differ on the concentration measure $\hat{C}$. The difference on the processing time between these conditions was expected, because the mixed condition is more complex and because all uncontrollable disturbing sources, as for instance errors and expectancy effects, will have a minor influence in a condition that allows the subject to withdraw from the task now and then. On face value, however, it was also expected that the spaced condition would have the largest effect on the distraction time, since the rest periods could be made as long as necessary to make the mental processors recover fully, whereas the alternation of tasks seems less effective in reducing the inhibition. Nevertheless, our results suggest that the alternation of tasks benefits the concentration as much as regular rest periods do.

8.2 Part II: the application

8.2.1 Disturbing factors: Task related factors

In most of the experiments mentioned in this study two choice RT tasks were employed. Stimuli were presented on a computer screen and responses consisted of pressing one of two buttons. The RSI was always long enough for the subject to see that a new stimulus was presented (RSI of 5 msec.).

Application of the concentration measure requires that the processing time per trial or per block of trials, if that is the unit of the analysis, is constant. This assumption puts a heavy load on the construction of the task. Disturbing factors affecting the processing time should as much as possible be controlled for.

Van Breukelen (1989b) summarized some well-known disturbing factors in two choice RT experiments. The three most important nuisance effects will be highlighted: (1) stimulus and response repetitions, (2) expectancy effects, and (3) post-error effects. For short RSIs stimulus as well as response repetitions result in faster responses than stimulus respectively response alternations. These effects can be kept under control relatively easily. For a start stimulus repetitions were not allowed in the experiments reported in this study. Response repetitions were handled by taking the RT of six trials as the unit of the analysis. Within each block of RTs two response repetitions could occur at the most. By and large the blocks of trials are equal with respect to the response repetitions.

More difficult to control, however, are the other two disturbing factors. The expectancy effect is controlled by making a YES answer as likely as a NO answer. Finally, the subject is requested to make no errors. Usually the error rate is quite low (below 5%), which means that the influence of the higher post-error RTs will be limited. For more details on this issue see Van Breukelen (1989b).

8.2.2 Disturbing factors: Subject related factors

A subject's strategy or attitude towards the task situation also determines the constancy or fluctuation of the processing time. We pick out just two factors that seem worthwhile to be treated in some length: (1) Learning, and (2) Instruction. A learning or practice effect results in decreasing processing times during task performance. Task instruction can change the processing time in two directions depending on a bonus for precision or a bonus for speed.

8.2.2.1 Learning

In the Jansen and Van Breukelen study (1987, see chapter 4 of this thesis) in which the Pauli task was employed, an unexpected strongly decreasing curve was found in the so-called carry condition. The carry condition was the only condition that contained different stimuli. Instead of digit additions with sums below 10, in the carry condition digit additions with a sum above 10 were used. It turned out that the subjects needed a lot of practice for these seemingly simple items. Since no practice series were administered for the carry condition, the processing time decreased during this condition. Some support for this statement could be found by inspecting the practice series of the no-carry condition, i.e. the condition with digit additions having a sum below 10. The majority of the RT curves of the practice series were decreasing (28 out of 32 curves) just as the curves of the carry condition (22 out of 32). The baseline condition which was administered just after the practice condition already had an increasing trend (26 increasing curves against 6 decreasing curves). This points to the conclusion that for these kinds of items and conditions one practice series may be sufficient.

Since the design of the Bourdon experiment of Van Breukelen and Jansen (Van Breukelen et al., 1987b) was the same as the design of the experiment just mentioned, it was possible to check the conclusion of the sufficiency of one practice series. The results for the practice and baseline series of the Bourdon task were almost the same as those of the Pauli task. A vast majority of the RT curves had a negative slope in the practice condition (26 decreasing curves against 13 increasing), whereas there was an even larger number of increasing curves in the baseline condition (32 increasing versus 8 decreasing).

These results support the notion that at least one practice series of trials is necessary to justify the assumption that the processing time is constant over trials in the experimental conditions. In all our experiments every experimental condition was preceded by at least one practice series.

8.2.2.2 Instruction: some experiments

TABLE 24

Number of increasing and decreasing RT curves per experiment

Experiment	increasing	decreasing
7		
massed	4	6
spaced	0	10
8		
massed	3	7
spaced	5	5
9		
massed	8	2
spaced	6	4

In the clinical setting a concentration measure is a useful tool for assessing the magnitude of an attentional deficit. To be sure that the measure developed within the

TABLE 25

ANOVA of the experiment 9

Variables	Massed	Spaced	F	df	p
RT_{Mean}	5.49	5.24	25.83	1,8	<.001
C	6.71	7.46	0.60	1,8	>.05
$RT_{Variance}$	0.26	0.13	3.60	1,8	>.05
$RT_{Minimum}$	4.67	4.53	3.43	1,8	>.05
Error rate	20.80	17.62	1.03	1,8	>.05

inhibition theory is feasible and valid we tried to replicate the massed versus spaced experiments of Van Breukelen and Jansen using other equipment. We administered the Bourdon task on an Apple II plus PC with student volunteers as subjects (for the apparatus and procedure see Bruggeman, Eling and Jansen, in press).

Three successive experiments (no. 7, 8, and 9) were run in each of which participated 10 different students. The design was the same for each experiment: five subjects first got the massed condition and then the spaced condition and the other five subjects got the opposite sequence of conditions. Each condition consisted of 270 practice trials followed by 630 experimental trials. Rest periods in the spaced condition were given after each ninth trial.

The results of experiment 7 were disappointing. The massed and spaced condition differed on none of the task variables. Moreover, all curves of the spaced condition and most of the curves of the massed condition were decreasing (see table 24).

The instructions for experiment 8 were slightly different from experiment 7. Subjects were now requested to use the rest periods as well as possible. They should work fast but accurate during the periods of work, and they should take as much as rest as necessary during the available periods of rest. The results of these instructions were first of all that in all of the conditions the error rate increased drastically, especially for one of the two sequence groups. Although this time the differences between massed and spaced were in the expected direction on all the task variables, no significant massed versus spaced effect was found. Moreover, most of the RT curves in the massed condition were decreasing (see table 24).

A last attempt to find the expected massed versus spaced effect was approached in one more experiment (no. 9) as follows. First, the block size was reduced from nine to six trials. Consequently, the total number of trials per series was smaller: 180 trials for the practice series and 420 trials for the experimental series. Further, explicit instructions were now presented on a sheet of paper instead of being given verbally.

The results of experiment 9 are in line with the findings of Van Breukelen and Jansen. The majority of the curves are increasing in the massed condition (see table 24) and also the residual variance is significantly increasing in the massed condition, $F(1,16)=6.79$, $p<.05$. Further, all effects on the task variables are in the expected direction but only the RT_{Mean} differs significantly between the massed and the spaced condition (see table 25).

Discussion. Given the predictions of the inhibition theory with respect to the increase in the RTs and to the difference between massed and spaced, the results of experiment 7 were rather discouraging, the results of experiment 8 were acceptable except for the large number of decreasing curves in the massed condition, and the results of experiment 9 were satisfactory. This last experiment differed from the other two on three points: (1) the instruction was given on a sheet of paper, (2) the rest periods were given after each sixth trial instead of after each ninth trial, and (3) the total length of the series was reduced from 630 trials to 420 trials.

It was possible to check whether the length of the trial series was responsible for the large number of decreasing RT curves in the first two experiments. For this purpose we reanalyzed the data using only the first 40 block RTs which implies that only the first 360 trials were considered. The number of decreasing and increasing RT curves turned out to be exactly the same for the 40 RTs as for the original 70 RTs. Also the ANOVA results were about the same for these shorter time series.

It is difficult to discriminate between the other two experimental factors which were different in experiment 9. It is, however, obvious that the altered administration of rest periods did not affect the massed condition. Therefore, we state that the written instruction is the most likely cause for the larger number of increasing RT curves in experiment 9. It is thinkable, that the subjects worked more concentrated from the start of the trial series in experiment 9 due to the instruction which stressed the point of working concentrated. On the other hand, the difference found between massed and spaced in experiment 9 could be due equally likely to the instruction as to the higher frequency of rest periods in the spaced condition.

8.2.2.3 Some conclusions

The learning factor seems relatively well controllable. However, at least one practice series of reasonable length is necessary to acquaint a subject with both the items and the condition.

More difficult to control is the instruction to the subjects. The standard formula is: *'work as fast as possible, but make no mistakes'.* This instruction can be modified by urging the subject to work concentrated. An additional tool which was used by Jansen and Roskam (1989), but also by Van Breukelen and Jansen (Van Breukelen et al., 1987b) was feedback after the practice series. A person who made too many errors could be told to work more accurate, and a person working too slow could be encouraged to work faster.

Although it may be too obvious even to mention it, we want to stress that instructions should be given on a standard form, not too extensive, but certainly not too short. All these seemingly trivial details of the testing situation should as much as possible be standardized.

Besides changing the instruction, also the number of trials per block was altered in the experiment 9. The block size, however, will have no influence on the shape of the time series in the massed condition, since in that condition trials are presented in one chain. The spaced condition could have benefited from getting a rest period more often. In our opinion, however, it was the better and more standardized way of instructing the subjects that led to the results of the last experiment.

8.2.3 A standard procedure for concentration testing

This section contains a proposal for standardizing the procedures of concentration testing. This proposal is built around the measure of concentration, $\hat{C}$, as given in equation [30]. $\hat{C}$ depends foremost on the assumption that the processing time is constant. Task construction and administration both aim at making this constancy assumption plausible and tenable.

8.2.3.1 Task construction

Two choice RT tasks are always recommended because the response set of these kind of tasks reduces the possible source of error due to response programming to a minimum. Time spent on motor programming is about the same on every trial. Further, the sequence of response repetitions and alternations can be kept under control. As the unit of analysis we suggest six consecutive trials. Each block of six trials contains three YES and three NO answers. The order of these responses within a block is chosen at random.

The choice of the items can be made under the following restrictions: (1) items should belong to a specific domain of knowledge or ability, (2) the answers to the items should be trivial to all the testees for whom this test is meant, (3) at least one practice series should be given to acquaint a testee to the testing situation. The items will, therefore, be rather simple two choice items, such as the Bourdon items, the Pauli items, or the items of the letter matching task. The investigator should as much as possible ban the variability of processing time.

8.2.3.2 Administration

A written or at least standardized instruction should be given stressing the importance of working fast but accurate. The testee should be fully aware of the fact that his concentration is being measured, and that the testee himself is responsible for his achievements.

At least one, and preferably more practice series of considerable length should be administered to the testee before he starts with the actual test. It is technically possible to analyze the data of a testee immediately upon the ending of a series of trials. In this way the opportunity is available to judge the data of a testee and to decide that he or she should be given another series of trials because the time series was still decreasing or because the testee made too many errors. The problems that arise in this kind of tailored testing go beyond the scope of the present study. At this stage we merely point at a possible administration of a concentration test.

8.2.3.3 Analysis

The most important variable in the analysis is obviously the concentration measure $\hat{C}$. To calculate $\hat{C}$ we need to estimate the processing time. The processing time parameter in the IMAX model is A. A can be estimated with the equations [24] and [26] from chapter 3. Within the inhibition theory A only attains acceptable values if the RT curve is non-decreasing. In case a RT series is immediately analyzed after the testee has finished it is possible to give as many series as is necessary to have only increasing RT curves. This means that it is in fact feasible to use A as the estimate for the processing time. In that case the concentration measure $\hat{C}$ of equation [29] is recommended.

As was already mentioned in an earlier section the processing time can also be estimated by $RT_{Minimum}$. Unlike A, $RT_{Minimum}$ always has an acceptable value for the processing time, although $RT_{Minimum}$ is slightly upward biased. In those cases in which decreasing RT curves do occur, the processing time is estimated better by $RT_{Minimum}$, and $\hat{C}$ is then estimated better by equation [30].

It should be stressed at this place that $RT_{Minimum}$ as an estimate for the processing time in case of a decreasing RT curve is nothing else than just not too bad. From a theoretical point of view a decreasing RT curve most probably implies a decreasing processing time, assuming that the subject did not take a long rest period during task performance, and given that no rest periods (or alternating tasks) are administered. Therefore, the assumption of a constant processing time is violated, and an unbiased estimate of A and C can never be given. The implication of this conclusion is that the administration of a task should be repeated until the obtained RT curves are increasing.

The other task variables, such as trend in RT_{Mean} and trend in $RT_{Variance}$ or the overall error rate, only serve to check whether there are any peculiar or strange phenomena in the data.

8.2.4
The validity of the proposed measure of concentration

What criteria can be used if we want to investigate the validity of a concentration measure? Since no strict definition of concentration is available, we have to rely on the opinion of neuropsychologists and psychiatrists in the professional setting.

Certain attentional deficits can be labelled as concentration disorders. After extensive examinations field workers such as neuropsychologists and psychiatrists are able to categorize patients as having a concentration disorder or not having such a deficit. Bruggeman, Eling and Jansen (in press) used this kind of classification of patients for their experiment, which will be reported below.

Children are believed to show large differences in concentration. Two experiments will be reported on that particular population. Finally, some explorative data are shown on the correlation between variables within a concentration test and between tests with different kinds of items.

8.2.4.1 Subjects with attentional deficits

Bruggeman, Eling, and Jansen (in press) reported an experiment in which they investigated the discriminating power of $\hat{C}$ in both a pencil-and-paper and a computer version of the Bourdon task. Subjects were 21 patients with closed head injuries. They all had to go through several examinations. A group of professional psychologists then judged whether a patient suffered from a concentration disorder, which stood for a deficit in maintaining the attention to a specific task for a longer period of time. A total of 11 patients were classified as having a concentration disorder. The other 10 patients served as a control group.

All patients had to complete both the pencil-and-paper Bourdon and the computer Bourdon. The pencil-and-paper version had two lines of practice, whereas there was a considerable amount of trials for practice on the computer. The results were as follows. On the computer version of the Bourdon task patients with attentional deficits scored a larger RT_{Mean}, $RT_{Variance}$, and a lower $\hat{C}$ than the other patients, but they did not differ on $RT_{Minimum}$, the estimator of the processing time. Further analysis showed that $\hat{C}$ was in fact the best discriminating variable. These results fit exceptionally well into the framework of the inhibition theory, since the patients were expected to differ only on the concentration measure, and not on the processing time. This turned out to be the case.

The data of the pencil-and-paper version, however, yielded no differences between the two patient groups on $\hat{C}$, but on the other hand a significant difference was found on $RT_{Minimum}$. Taking only the results of the pencil-and-paper Bourdon into account the conclusion should be that the patients do not differ in their ability to concentrate, but they differ in their processing capacities. However, it is very well possible that in this case $RT_{Minimum}$ was a very bad estimator of the processing time, since the subjects got only two lines of 24 items for practice, and since the circumstances of a pencil-and-paper administration are harder to keep under control.

8.2.4.2 Concentration among children

Van Breukelen and Souren (1990; Van Breukelen, 1989a) reported an experiment in which 18 children with learning disabilities participated. A massed and a spaced condition of the pencil-and-paper Bourdon task were administered after some extensive practice series. The results were astonishingly similar to the results with a sample of adults reported by Van Breukelen and Jansen (Van Breukelen et al., 1987b), of which we gave a summary in earlier section. The individual RT curves were almost all increasing in the massed condition (17 out of 18 were increasing), opposed to only 5 increasing curves in the spaced condition. The children clearly gained from the opportunities to take a rest. RT_{Mean}, $RT_{Variance}$, and $RT_{Minimum}$ were all significantly lower in the spaced condition, and $\hat{C}$ was significantly larger in the spaced condition, $F(1,17)=54.55$, $p<.001$.

The generality of this massed versus spaced effect within a population of children can be further illustrated by an experiment of Bosman, Jansen, and Vloet (in prep.). Within the context of a reading experiment 60 children also got a massed and spaced series of a letter matching task (Posner, 1978).

TABLE 26

Massed versus spaced in a sample of children (rearranged from Bosman et al., in prep.)

Variables	Massed	Spaced	F	df	p
RT_{Mean}	3.66	3.38	12.32	1,118	<.001
$RT_{Minimum}$	2.43	2.37	1.23	1,118	>.05
$RT_{Variance}$	1.14	0.85	2.24	1,118	>.05
C	2.29	2.74	9.07	1,118	<.01
Error rate	3.16	2.55	5.32	1,118	<.05

Even though the series were quite small (48 practice trials followed by an experimental series of 64 trials), a clear massed-spaced effect was found: RT_{Mean},

$RT_{Variance}$, and the error rates were significantly smaller in the spaced condition, and $\hat{C}$ was significantly larger in that condition. Only $RT_{Minimum}$ did not differ between the two conditions. A summary of the results is given in table 26. These results are again very nicely in line with the inhibition theory.

Bosman et al. (in prep.) administered also several psychological tests. Among others the Raven Matrices to measure intelligence, a verbal IQ test, and a reading comprehension test were employed. Even though a multitude of test variables were available, none of the variables of the concentration test showed a correlation of some importance with any of the test variables.

8.2.4.3 Correlational studies

A proper measure of concentration should have an acceptable stability over a short span of time and, further, this measure should not be too task specific. In an explorative manner a few data can be reported with respect to this issue.

In experiment 6 of this chapter the subjects received the massed condition of the Bourdon task twice with a time interval of at least a couple of days and two weeks at the most. The correlation of $\hat{C}$ between these two occasions was 0.70 (N=16). To get some idea of the relevance of this correlation all correlations among the task variables of experiment 6 are presented in table 27. This table shows that the correlation of $\hat{C}$ between these two conditions is about as high as the correlations of RT_{Mean} and $RT_{Minimum}$, which variables are known for their large correlations.

Knowing that RT_{Mean} and $RT_{Minimum}$ decreased from the first to the second administration of the Bourdon task, whereas $\hat{C}$ remained relatively at the same level (see table 23), it is even more surprising to know that the correlation of $\hat{C}$ is also high. The implication, then, is that $\hat{C}$ is stable per subject and between subjects over a short period of time. The implication, also, is that $\hat{C}$ is relatively unaffected by a learning effect.

In the experiments of Van Breukelen and Jansen (Van Breukelen et al., 1987b) the same subjects got both the Bourdon task and the Pauli task. The correlation of $\hat{C}$ in the massed conditions of the two experiments was 0.50. This correlation is quite substantive if we take into account the magnitudes of the correlation of the other task variables between the two experiments (see table 28).

Of interest to the present purpose are also the correlations of $\hat{C}$ with the other task variables within and between tasks. $\hat{C}$ correlates relatively high with $RT_{Variance}$

TABLE 27

The correlations among the variables of experiment 6 between the first and second Bourdon massed (N=16)

		Second Bourdon				
		Mean2	Var2	Min2	C2	Error2
First	Mean1	0.73	*	0.69	*	0.45
Bourdon	Var1	0.40	0.49	0.42	-0.40	0.50
	Min1	0.56	*	0.74	*	*
	C1	-0.36	-0.44	*	0.70	-0.58
	Error1	*	*	*	*	-0.21

Note. Apart from the diagonal, only correlations over 0.40 are shown.

and relatively low with $RT_{Minimum}$ as was to be expected from the inhibition theory. These correlations are not only observed within a task, but also between tasks, as is shown in table 28.

8.2.4.4 Some conclusions

The few experimental results gathered in the light of the validity of $\hat{C}$ are very encouraging. $\hat{C}$ discriminates between patients with and without attentional deficits, if the test situation is well controlled. Further, normal children and children with learning problems are able to benefit from regular rest periods. This last result supports the inhibition theory and it, therefore, also strengthens the applicability of $\hat{C}$ as a measure derived from this theory. Finally, $\hat{C}$ appears to have a fair stability and to be relatively task independent.

8.3 Part III: General discussion

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TABLE 28

Correlations between Bourdon and Pauli (N=30) and within the Bourdon task (same N=30)

		PAULI TASK				
		Mean	Var	Min	C	Error
	Mean	0.69	0.70	0.63	*	*
BOURDON	Var	*	0.52	*	-0.43	*
TASK	Min	0.71	0.61	0.70	*	*
	C	-0.40	-0.49	*	0.50	*
	Error	*	*	*	*	0.35

		BOURDON TASK				
		Mean	Var	Min	C	Error
	Mean	xx				
BOURDON	Var	0.79	xx			
TASK	Min	0.88	0.54	xx		
	C	-0.67	-0.70	*	xx	
	Error	*	*	-0.45	*	xx

where Mean = RT_{Mean}
Var = $RT_{Variance}$
C = $\hat{C}$
Min = $RT_{Minimum}$
Error = Error rate

Note. Apart from the diagonal, only correlations over 0.40 are shown.

concentration disorders or attentional deficits is mandatory. Some tests of concentration are available, but a theory underneath the testscores lacks. A theory is presented in this study which includes a measure for concentration.

The inhibition theory basically states that a RT on a trial of a mental task consists of processing time and distraction time. As was stated several times, distraction time is interpreted as time spent on all other mental activities than on those improving task performance. The more time is consumed by other mental activities, the less efficient a task is performed and, therefore, the less concentrated a person works. This idea of efficiency in mental processing also leads to the concentration measure proposed in this study: $\hat{C}$ is the ratio of the effective mental processing and the ineffective mental processing.

8.3.1 The concentration measure C

There exists a theoretical objection which could be raised against the proposed concentration measure $\hat{C}$. This objection is that the value of $\hat{C}$ depends on the length of the test. If a time series would be stationary from the beginning (as was assumed in the Poisson Erlang model of Pieters and Van der Ven, 1982), $\hat{C}$ would definitely be independent of the length of the test. However, since the time series are supposed to be increasing the total amount of distraction time depends on the rate by which the distraction time increases at the start of the series and on the length of the test.

There are at least two ways out of this problem. First, C could be redefined as the ratio of the processing time and the stationary amount of distraction. In terms of the model parameters this would lead to equation [32].

$$C = \frac{A}{I_{max} A \delta^{-1}}$$

$$\text{which equals } C = \frac{\delta}{I_{max}} \qquad [32]$$

However, in those cases in which the concentration measures of equations [29] and [32] could be measured, their correlation was very high, $\rho=0.96$ for the Bourdon massed condition with $N=37$, and $\rho=0.95$ for the Pauli massed condition with $N=30$ (see Van Breukelen et al., 1987b). These correlations imply that given that a curve increases, the first increasing part of the RT curve does not have that great an impact on the concentration measure. So empirically speaking the length of a test does not seem to have a large influence on $\hat{C}$.

A second solution to the problem of the test length dependency of $\hat{C}$ is the consideration that a concentration measure indeed could be test length dependent. It seems not unreasonable to assume that some person has a high but short lasting concentration, whereas another person has a lower but longer lasting concentration. The consequence is obviously that we do not measure the concentration per se of a person, but that we measure the concentration given a certain test length. Thus, we could measure the concentration for a short test along with the concentration for a long test. It remains in this way an empirical question whether the concentration is test length dependent.

8.3.2 *The test situation*

It is suggested that the inhibition mechanism is most prominently present in a testing situation in which the task contains equivalent and well-practiced items and in which the administration follows strict rules. Another way of putting this is that $\hat{C}$, the concentration measure, will only be valid if the items of the test are equally simple, and if no learning effects or speed-accuracy fluctuations are present.

Empirical evidence supports the idea that $\hat{C}$ can be obtained according to the restrictions just mentioned and that in those cases $\hat{C}$ turns out to be a promising measure of concentration.

Improvement of the measurement of concentration can be achieved by adjusting the testing situation. Besides the requirements for task construction and task administration it is proposed to give another series of trials, in those cases in which the RT curve of the series just analyzed is still decreasing. It seems also necessary to require that the error rate is low and stationary (or at least non-decreasing).

Since these problems are merely practical, it is very well possible that a standard procedure for concentration testing using $\hat{C}$ as its index will be available in the very near future.

9 CONCLUSIONS AND SUMMARY

In this final chapter the inhibition theory is evaluated in the light of the empirical results gathered in this thesis and gathered from other sources. Some consideration is given to the concept of inhibition and to different kinds of modeling of this inhibition concept. Two extensions of the INHIBITION model are presented. The mixed inhibition model supplies an opportunity to extend the inhibition theory. It seems possible to derive from experimental data of a homogeneous versus mixed paradigm the conclusion that tasks employed in the mixed condition share more or share less mental processors. Concludingly, the mathematical model approach is discussed.

9.1 A general evaluation of the inhibition theory

9.1.1 The inhibition theory

The inhibition theory states that the probability (hazard rate) of an interruption, or 'inhibition' of the currently processed task, increases with processing time. We can call this 'inhibition', 'overload', 'mental fatigue', 'satiation', or any other term which seems appropriate to describe it. The time during which task-processing is thus stalled, is called distraction. During distraction, the inhibition decreases. Our experiments indicate that this time can be filled by processing an alternate task. It appears now logical to assume that a similar accrueing of inhibition happens to the alternate task. Thus, the inhibition is task-specific: whatever it is that is active during task processing can be called a task-processor; it appears to need recovery from work. If there is no alternate task, distraction time can be filled by any task-irrelevant mental activity.

The question why the inhibition mechanism should work this way from, for instance, a physiological point of view, falls beyond the scope of this thesis, and this question is also irrelevant at this stage of research. The theory proposes an inhibition mechanism that works this way. A major point on which this theory differs from former theories, is that it was formalized into a mathematical model. The so-called INHIBITION model of Van der Ven and Smit (Van der Ven, Smit & Jansen, 1989; see also Van Breukelen et al, 1987b) was described in detail in chapter 3.

At least two empirical consequences follow from that description of the INHIBITION model : (1) a negative autocorrelation is predicted in a continuous RT series. In a short RT little distraction has occurred, which means that for the next trial the inhibition remains relatively high. As a consequence the probability of a distraction is relatively high, which makes it more likely that the duration of the next RT will be relatively long. And (2) if the initial inhibition I_0 is below its stationary expectation (which equals $\mu_1\delta/\mu_2$), then the distraction time will be low at the beginning of the task and, consequently, $E(RT_k)$ and $\sigma^2(RT_k)$ will show an increasing trend, and they will become stationary in the long run.

As was shown in chapter 3, mathematical equations for the increase of $E(RT_k)$ and $\sigma^2(RT_k)$ can be easily derived from the IMAX model, a simplified approximation to the INHIBITION model. However, the IMAX model predicts no autocorrelation.

In several experiments these three predictions (negative autocorrelation, increasing RT, increasing RT-variance) were tested. Until now no convincing evidence is found that the RTs in series of trials are negatively autocorrelated. But an increase in the RTs and an increase in the residual variance is found in a number of experiments. A summary of these results is given in the next two sections.

9.1.2 The emperical evidence, part I

9.1.2.1 Massed versus Spaced

In two experimental studies Van Breukelen and Jansen (1987a) administered a massed condition, in which trials were presented with a very short response-stimulus interval, and a spaced condition, in which regular rest pauses of at least three seconds were induced.

The INHIBITION model predicts for each subject a negative exponentially increasing RT curve in the massed condition. Assuming that the inhibition will drop considerably during the rest pauses, a stationary RT curve is predicted for the spaced condition. Therefore, it was hypothesized that far more subjects would show an increasing RT curve in the massed condition than in the spaced condition.

Table 29 shows that in the massed condition a vast majority of the individual RT curves is increasing. In the spaced condition the majority of the curves is decreasing. These results hold for both tasks. As was also reported by Hylan and Kraepelin (1904), Bills (1931), Sanders and Hoogenboom (1970) and others, the performance in the spaced condition was overall far better than in the massed condition. See chapter 4 for a further discussion of the results of the massed versus spaced

TABLE 29
The number of increasing and decreasing individual time series per condition per task

TASK	CONDITION	INCREASING	DECREASING
BOURDON	MASSED (N=40)	37 (13)	3 (1)
	SPACED (N=40)	17 (0)	23 (2)
PAULI	MASSED (N=32)	30 (15)	2 (0)
	SPACED (N=32)	9 (2)	23 (5)

NOTE. Between brackets: the number of significantly increasing, or decreasing curves are given

experiments.

Additional evidence on the massed versus spaced effect was found on a letter-matching task with children aged 8 to 10 as subjects (Bosman, Jansen & Vloet, in prep., see chapter 8). Further, Van der Ven et al. (1989) reported a vast majority of increasing curves in a massed administration of a pencil-and-paper version of the Bourdon task.

9.1.2.2 Homogeneous versus Mixed

A second line of testing the inhibition mechanism was the homogeneous versus mixed condition. These conditions were administered in a massed version. Homogeneous means within this context that the subject is given only trials with stimuli of one kind of task, e.g. the Bourdon task. In the mixed task condition stimuli of two or three different tasks are randomly alternated, e.g. alternating Bourdon trials with trials of a letter-matching task.

The theoretical considerations that led to the experimental design of a homogeneous and a mixed condition, are as follows. Within the period of time that the processor of one task is active, the processor of another task can recover. This last processor should be irrelevant to the first task, but is not irrelevant to the overall task performance. For simplicity we consider only one mental processor per task. The reasoning in case of more than one processor is analogous, only then one should take account of the fact that the processors of the two tasks may partially overlap.

In chapter 5 (Jansen and Roskam, 1989) three experiments on the homogeneous tasks versus mixed tasks issue were reported. In the mixed condition two tasks were alternated. Since it was hypothesized that the time used by the second task served the processors of the first task to recover, Jansen and Roskam predicted that the time series for the mixed conditions would be stationary, whereas the time series for the homogeneous conditions were expected to increase.

The results of all three experiments confirmed the predictions. Figure 10 of chapter 5 illustrates the homogeneous tasks versus mixed tasks effect. The RT curve denoted Homogeneous is the average time series of three homogeneous tasks (the Bourdon task, the Pauli task, and a letter-matching task). The Mixed RT curve is the average time series of the three possible mixed conditions of two tasks each. It is clearly visible that the RT curve of the homogeneous tasks increases more than the RT curve of the mixed tasks. The conclusion of these experiments was that distraction time becomes less if two tasks are alternated. A more general conclusion is that inhibition is task-specific.

9.1.3 The empirical evidence, part II

Van Breukelen and Jansen (see Van Breukelen et al., 1987b) supplied evidence in favor of the inhibition theory through the massed versus spaced paradigm. The performance improving effects of the rest pauses were already found by Hylan and Kraepelin (1904). Bills (1931) tried to support his idea that mental blocks serve as necessary periods of rest, by showing that artificially induced rest pauses improved performance. Bertelson and Joffe (1963) yielded additional evidence in favor of this idea, as they found that RTs increase before a mental block and drop afterwards. Note that this last mentioned empirical result is exactly predicted by the INHIBITION model. Further, the concept of mental blocks is perfectly in line with the inhibition theory as presented in this paper. Finally, it can be pointed out that Parasuraman consistently found that performance on a high event-rate task decreases more rapidly on a low event-rate task. Since a low event-rate task gives a subject more time to rest than a high event-rate task, this result is also predicted by the inhibition theory.

From the perspective of the second category of explanations the massed versus spaced effect is also expected. Whereas massed trials do not give any opportunity to the human system to reload the attentional capacity, this capacity can be restored (for some unspecified reason) during rest periods. This would explain why loss of attentional capacity only affects performance in massed trials.

A second line of evidence is the effect of homogeneous tasks versus mixed tasks. Robertson and Bills (1926) already showed that performance on a heterogeneous task is superior to performance on a corresponding homogeneous task. In the experiments of Jansen and Roskam (1989; this thesis chapter 5) this same result was consistently found under severely controlled conditions. Especially these empirical results are hard to explain by other theories. The inhibition theory predicts this effect, since only the task specific mental processors are assumed to get inhibited.

Whereas it can be claimed that the loss of attentional capacity hypothesis can cope with the results on massed versus spaced conditions, it is hardly thinkable how the results on the homogeneous versus mixed conditions can be explained as losses in attentional capacity. For one thing, more attentional capacity is demanded in case of mixed tasks. It seems, further, reasonable to expect that the effect of distracting thoughts will be more severe if the spare capacity of attention is smaller. Therefore, a more decreasing performance curve should be expected for the mixed condition than for the homogeneous condition. However, the experimental results point in the opposite direction.

9.1.4 The conclusion

In chapter 2 we ended our discussion on the possible candidates for explaining performance decrement with time on task with the conclusion that only two theories were worthwhile considering: (1) the inhibition theory, and (2) the loss of attentional capacity theory, or, more generally, the limited resources theory. In chapter 5 it was argued that this latter theory was not capable of coping with the results found in the homogeneous versus mixed tasks experiments. Due to this reason we conclude that the inhibition theory yields the best explanation for the observed decrement in performance on repetitive tasks that do not take longer than about 15 minutes to complete.

There is, however, a critical experiment to test the inhibition theory which has not been executed until now. If two tasks are alternated in a very strict sequence order, say ABABAB, the inhibition theory would still predict that the performance in the mixed condition will be better than in the homogeneous conditions. It might, though, be the case that the unexpectedness of the stimuli (task) to come is of critical importance for the good performance in the mixed condition. In that case, a theory based on the orienting response would be more valid than the inhibition theory as presented in this thesis.

9.1.5 *Is the empirical evidence good enough?*

The analyses contained two classes of variables: (1) trend variables (trend in E(RT), trend in residual variances), and (2) RT variables (RT_{Mean}, $RT_{Variance}$, $RT_{Minimum}$, $\hat{C}$, and the error rate).

The major evidence in favor of the inhibition theory concerns: (a) the increasing trend in RT and in residual RT variance, and (b) the differences in $\hat{C}$ and $RT_{Variance}$ between experimental conditions. It can be argued that the differences found in $\hat{C}$ and $RT_{Variance}$ are at least partly consequences of the differences in the trend of the individual time series. The question to be attacked, then, is: *Are there any alternative theories besides the inhibition theory that can account for these differences in RT trend between conditions?*

The answer is that we could not find any good alternative for the inhibition theory. Searching for experimental artifacts it could be hypothesized that for the homogeneous versus mixed paradigm the mixed conditions were not overlearned, and that, therefore, the increase in RT is covered by a learning effect. However, the experiments of chapter 5 falsify this hypothesis. The results of these experiments were even in complete disagreement with this last hypothesis. In those experiments, in which the subjects have had more practice in the mixed conditions than in the homogeneous conditions, the differences between the homogeneous and mixed conditions were more in line with the predictions of the inhibition theory than in the experiments in which the subjects have had relatively less practice in the mixed conditions.

To sum up, if the empirical evidence which is given in the experiments of this thesis and which is in favor of the inhibition theory, should be discredited because of experimental artifacts, this would mean that an alternative explanation can be given for the differences in RT trend between the homogeneous and mixed conditions and also between the massed and the spaced conditions. Until now, the inhibition theory is the only one that can cope with these diverse experimental results.

The value of the empirical evidence becomes even stronger if it is taken into account that in most of the experiments reported a trend in the residual variance is found in the massed conditions, as was predicted by the inhibition theory. It can be stressed that the trend in the residual RT variance is not an artifact of the trend found in RT. In other words, trend in the residual RT variance is an additional source of information.

Inhibition and concentration. We observed that the differences in $\hat{C}$ are independent of differences in $RT_{Minimum}$. For instance, contrasting massed and spaced conditions it was found that $RT_{Minimum}$ was lower in the spaced conditions, whereas $\hat{C}$ was lower in the massed conditions. However, the results for the homogeneous versus mixed conditions showed that although $RT_{Minimum}$ was higher in the mixed conditions, still $\hat{C}$ was also higher in the mixed conditions.

In most of the experiments reported it was found that the correlations between $RT_{Minimum}$ and $\hat{C}$ were near zero. Therefore, it can be stated that the processing time and concentration are independent. From a theoretical viewpoint, it seems quite plausible to maintain that concentration and speed of processing are independent. Observing this independence, then, gives additional credit to the inhibition theory.

9.2 Considerations on the concept of inhibition

The concept of inhibition as considered in this study is in line with the concept of 'internal inhibition' of Pavlov (1927), with the term 'reactive inhibition' of Hull (1943), with the 'stimulus inhibition' of Eysenck (1963), and with the 'neural habituation, or inhibition' of Mackworth (1969). Inhibition is the impossibility to maintain an initial speed of processing over time on task. In our description the task related mental processors get inhibited and need a recovery period before being activated again. Given the formalization of the inhibition mechanism in the INHIBITION model we are able to derive fairly exact predictions in specific experimental situations. In case of the massed versus spaced conditions and in case of the homogeneous versus mixed task conditions this INHIBITION model turns out to do a reasonable good job in predicting differences between conditions.

For answering the question whether the inhibition theory is `psychologically plausible` or not, we have to speculate on the organization of mental processing. The starting point of this speculation is the knowledge that we have of the transmission of information along the neural networks.

One single neuron transmits information purely by the principles of inhibition and excitation (or activation). Considering higher order mental activities as the activation of a whole bundle of neurons, the inhibition of this bundle can develop gradually assuming that the onset of activation of these neurons follows a stochastic process. Reasoning in this way one could claim that viewing the inhibition mechanism at a higher level as a quasi-continuously process in which the mental processing is randomly slowed down by inhibitions of the separate neurons, may be psychologically more sound than viewing the inhibition mechanism as a two-state all-or-none process, i.e. a process versus non-process mechanism.

However, the only reason for leaving the present two-state model should be that the quasi-continuously model is empirically more powerful in predicting differences among conditions than the two-state model. For the moment there exists no evidence supporting that hypothesis. Moreover, if we were to formalize mathematically a quasi-continuous process of which the speed is stochastically variable, it might well turn out to be data-equivalent with a two-state model, where processing halts and resumes at random intervals.

In conclusion, the concept of inhibition implies always a difference in activation level, like active versus inactive, or more active versus less active. A choice between these two combinations seems a matter of taste. The INHIBITION model is just one worked out description of the influence of the inhibition mechanism on mental processing with time on task. It has received enough empirical support to believe that we indeed are on the right track.

9.3 Extensions of the inhibition theory

In the present formulation (Chapter 3) the INHIBITION model is stated for a massed condition of a homogeneous task. For a spaced condition the rest period between the blocks of trials should be incorporated into the model. For the mixed tasks condition the processing of the second task should be considered.

We shall outline such an extension by discussing three steps to be taken. First, the hazard rate of shifting from processing to distraction will be formulated in terms of the new model. Secondly, the consequences of the new model will be derived in a more or less intuitive way. Thirdly, some possibilities to test the model will be discussed.

Usually, deriving the consequences of the formulated hazard rate will be conducted by elaborating on the mathematics. However, the mathematical equations which are necessary to predict the expected RT on trial k or any other moment of the RT distribution, are very hard to derive, if not impossible. A second best solution for estimating the consequences of a specific formalization would be to perform some simulations studies that would predict the RT curve and its variance. For the following models these simulation studies still need to be done.

9.3.1 A spaced inhibition model

The hazard rate function indicating the rate of shifting from processing to distraction can best be described as follows:

$$I(t) = max[0\ ,\ I_0+\mu_1 P-\mu_2 D-\mu_2 R] \qquad [33]$$

Equation [33] reads that the inhibition increases with the accumulated processing time, P, and decreases with the accumulated distraction time, D, and with the accumulated time of rest, R. For mathematical derivations with respect to the expected RT and also for simulation studies, R depends on the experimental design, and can be considered fixed.

Even with as little information as the hazard rate function, certain predictions can be made. If R is relatively large in relation to P, then $I(t)$ will drop to its initial value, and the incidence of distractions will stay very low. This implies that taking the block of trials as the unit for measuring RTs, the expected RT curve will be stationary. This result was found for the spaced conditions mentioned in chapter 4.

Another prediction that can be formulated, is that within a block of trials an increase in RT at trial level is expected. This effect is predicted because within blocks the INHIBITION model given in equations [11] through [14] of chapter 3, should hold, since the accumulation of R is zero within blocks. In chapter 4 it was reported that this increase in RT was actually found.

If R is relatively small in relation to P, then $I(t)$ will be hardly affected by R, and an increase in distraction time is expected, and, therefore, an increase in RT is expected. Until now, no experiment has been designed to test this hypothesis, but it seems reasonable to suppose a continuum from completely massed trials to completely spaced trials, and to predict that the increase in RT over trials will behave accordingly, i.e. a lessening increase the larger the rest periods between trials.

9.3.2 *A mixed inhibition model*

For a mixed condition, $I(t)$ must be specified per task. In the following specification the other task serves partly as a rest period for the first one.[10]

$$I_1(t) = \max[0\ ,\ I_0+\mu_1(P + P_1)-\mu_2(P_2+D)]$$

$$I_2(t) = \max[0\ ,\ I_0+\mu_1(P + P_2)-\mu_2(P_1+D)]$$

where P is time devoted to 'shared' processors,
P_1 is time for task 1 specific processors,
and P_2 is time for task 2 specific processors [34]

Equation [34] yields only a global sketch of how the mixed condition may be formalized. For a more exact description the following problems have to be dealt with:

- distractions can occur either during task one or during task two.
- processing time P_2 of equation [34] can only be 'executed' *after* the end of a trial of the first task. Vice versa the same accounts for P_1 and the second task.
- the processing times, A_1 for task one and A_2 for task two can differ.

Of major importance for some theoretical considerations on the mixed condition is the assumption that two tasks may overlap in their use of processors, as was already illustrated in figure 12 of chapter 5. To derive predictions from the mixed inhibition model, it has to be known beforehand if two tasks share some processors, and, in fact, it has to be known how much of the processing time of a task involves the common processor(s). Given these very unrealistic requirements, it seems that a mixed inhibition model will be extremely complicated.

[10] We are only dealing with a mixed condition consisting of two tasks.

However, the same 'reversed' logic can be used for the mixed inhibition model as for the Additive Factor Method as described in chapter 1. The objective in this case would be to discover the amount of common processors that two tasks share.

Given equation [34] for $I(t)$ and given that the individual processing times for the two tasks are about equal, it follows that the processors of task one profit most of P_2 if the second task employs different processors. In that case, the RT curve belonging to the first task will not be increasing. Since vice versa the same accounts for the second task, a stationary time series is expected for the total mixed task. However, if the observed RT curve of task one is found to be increasing, the conclusion must be that evidently both tasks make at least partly use of the same processors.

In chapter 6 an experiment was reported in which three apparently very similar tasks were administered. This experiment served as an example to investigate whether it is possible to deduce from the observed RT curves in mixed conditions the conclusion that two tasks share some processors or share none. The results of this particular experiment supported the idea that tasks can be discriminated on the kind of processors they require. The tasks with either words or digits as their stimuli seem to require a semantic processor, whereas the Bourdon task with dot patterns as its stimuli makes use of a figural processor.

A prerequisite for empirical success in discovering mental processors seems to be, however, that the task are essentially very similar, e.g. in the just mentioned experiment the three two-choice RT tasks only differed on the kind of stimuli that they contained.

9.4 Concluding remarks

Near the end of chapter 1 three goals of this thesis were formulated: (1) testing the empirical value of the inhibition theory, (2) developing a measure for concentration, and (3) showing the usefulness of the mathematical model approach.

The inhibition theory has been discussed sufficiently in the first part of this chapter. The conclusions are that the empirical results support the inhibition theory and that the concept of inhibition as used in this thesis is globally in line with the main stream of the psychological theories on inhibition. Moreover, the INHIBITION model can correctly predict the statistical properties of the RTs.

9.4.1 Mental speed and concentration

In chapter 8 the ratio of effective processing to ineffective processing was proposed as a measure of concentration. The more effective the processing the higher the concentration will be. In some applications this measure called $\hat{C}$ turned out to be a useful index for individual differences in concentration. Further, it can be stated that task construction and task administration need only mild improvements for an optimal measurement of concentration. Therefore, a standard procedure for concentration testing is expected in the near future.

The concept of Mental Speed has not received as much attention in this thesis as the concept of Concentration. However, if a researcher would want to use mental speed as an index for intelligence, as was done by Jensen (1982; see chapter 7), we would advice him to take $1/A$ as the measure for mental speed, and not $1/RT_{Mean}$ as is usually done. From the point of view of the inhibition theory mental speed is the inverse of the processing time, and, therefore, $1/A$ is the parameter for mental speed.

9.4.2 The mathematical model approach

In chapter 1 it was stated that the advantage of mathematical models over other forms of theories lies in their generality, their precision, and their deductive power. This statement was exemplified in chapter 3 by means of the INHIBITION model and related models.

The assumptions of the INHIBITION model restrict the applicability of the model to well-practiced, simple, repetitive tasks with massed trials. Given these restrictions precise predictions can be derived for each subject on each task. More specifically, estimated parameters from a first completion of a task could be used to predict exactly what RT is expected on trial k of a second series of trials for the same subject in the same condition.

However, this kind of precision is not the first desire of a researcher. He would be more than satisfied, if he could precisely predict the trend in the RTs, the trend in the variance of RT, RT_{Mean}, $RT_{Minimum}$, $RT_{Variance}$, the residual RT variance, and perhaps some derivative task-variable, such as $\hat{C}$ in case of the IMAX model.

The deductive power of a mathematical model is perhaps most importantly indicated by the examples of the spaced inhibition model and the mixed inhibition model, as outlined in the previous section. Although in these cases only a formalization is given of the hazard rate function, still predictions concerning the trend in RT, and the amount of distraction time can be derived. Through simulation studies additional predictions would certainly follow. This example indicates the usefulness of formalizing a theory.

The intention of formalizing a theory is, first of all, to derive testable predictions at the level of task variables and *NOT* in the first place to yield predictions at the level of the model parameters. Specific consequences, i.e. the unforeseen predictions concerning the task variables, may follow from global mathematical formulations of a theory. For instance, it is very informative to know whether a theory on RT data predicts an extremely large $RT_{Variance}$, homoscedasticity of the variances of the RTs, positive skewness of the RT distribution, or even a stationary RT series.

Very often, these kind of consequences are implicitly present in a verbally stated theory on RT data. The message which is delivered at this place, is to formalize the theory, even if it is in very global assumptions, because, as was already mentioned in chapter 1, "*the investigator can discover the consequences of his assumptions, some of which may not be apparent at all.*"

Appendix: A. **THE CORRESPONDING PARAMETERIZATIONS**

The parameterization used in this thesis was worked out by Roskam and is described in Van Breukelen et al. (1987b). The original parameterization was derived by Smit and was described in Van der Ven et al. (1989). This appendix shows the exact correspondence between these two parameterizations.

Whereas in the description of Roskam the parameters of the INHIBITION model are denoted A, μ_1, μ_2, δ, and $I_{(0)}$, the parameters in the description given by Smit are A, a, b, c, and Y_0. These latter parameters can be expressed by the former parameters. Only parameter A corresponds between these parameterizations. The equations specifying the exact relations between the parameters are further:

$$a = \mu_2/\mu_1 \qquad \text{[A.1]}$$

$$b = \mu_2/\delta \qquad \text{[A.2]}$$

$$c = \mu\delta \qquad \text{[A.3]}$$

$$Y_0 = (I_{(0)} - \delta\mu)/\mu_1 \qquad \text{[A.4]}$$

To illustrate the implication of a different parameterization we will describe the equations for $E(RT_k)$ and $Var(RT_k)$ as given by Smit in Van der Ven et al. (1989). Equations [12] and [13] of chapter 3 are the corresponding equations in the parameterization of Roskam.

$$E(RT_k) = A + a^{-1}A + a^{-1}Y_0(1-r)r^{k-1}$$

$$\text{where } r = e^{(-bA)}$$

$$\text{and } k = \text{trial number} \qquad \text{[A.5]}$$

$$Var(RT_k) = 2a^{-2}(bc)^{-1}(1-r) + 2a^{-2}c^{-1}Y_0(1-r)r^{k-1}$$

where $r = e^{(-bA)}$
and k = *trial number* [A.6]

 THE CONDITIONAL LEAST SQUARES METHOD

The IMAX model parameters could be estimated by either a generalized least squares (GLS) method or a conditional least squares (CLS) method. The IMAX model predicts a two-segmented function for the expected RTs:

$$E(RT_k) = \alpha + \beta(k-0.5) \quad \text{for } k \leq \theta$$
$$E(RT_k) = \alpha + \beta\theta \quad \text{else}$$

where θ *is the trial-number at which* I_{max} *is reached.* [B.7]

The GLS method minimizes the error sums of squares:

$$\sum_{i=1}^{\theta} (Y_i - (\alpha + \beta(i-0.5)))^2 + \sum_{i=\theta+1}^{n} (Y_i - (\alpha + \beta\theta))^2$$

with Y_i *is the observed RT at trial i* [B.8]

as a function of α and β for each value of θ=1,2,...,n. Henceforth, the least squares estimates of α, β, and θ are determined.

In the CLS method, first α and β are calculated for each θ=1,2,...,n.

Let $Y_{mean} = (1/\theta) \sum_{i=1}^{\theta} RT_i$, where $E(Y) = \alpha + \beta\gamma/2$,

and $Z_{mean} = (1/(n-\theta)) \sum_{i=\theta+1}^{n} RT_i$, where $E(Z) = \alpha + \beta\gamma$

then $\hat{\beta} = 2(Z_{mean} - Y_{mean})/\theta$

and $\hat{\alpha} = Z_{mean} - \beta\theta$ [B.9]

Now, equation [B.8] can be calculated for each θ=1,2,...,n and those α, β, and θ are taken as the best estimates for which the error sums of squares is minimal.

Van Breukelen (1989a,1989b) showed that the GLS method and the CLS method both yield fairly unbiased estimates for α and β, and that they gave almost the same goodness of fit. The advantage of the CLS method over the GLS method is that for the CLS method the stationary RT_{Mean} equals $\alpha+\beta\theta$, which is conceptually quite nice.

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Samenvatting

Dit proefschrift handelt over de theorievorming op het gebied van de menselijke verrichtingen op eenvoudige mentale taken. De belangrijkste factoren om deze verrichtingen op te beoordelen zijn de nauwkeurigheid en de snelheid, waarmee een taak wordt afgewerkt. Er bestaat een afhankelijkheidsrelatie tussen deze twee factoren. Verhoging van de snelheid heeft (meestal) tot gevolg, dat er meer fouten worden gemaakt. Terwijl een verhoogde nauwkeurigheid (meestal) alleen kan worden bereikt door meer tijd te gebruiken alvorens een respons te geven op een stimulus van de taak.

Centraal in dit proefschrift staat de snelheid, waarmee een taak wordt uitgevoerd. Om mensen op deze factor gelijkwaardig te kunnen vergelijken moet de nauwkeurigheid onder controle worden gehouden. De instructie, die de proefpersonen kregen bij de taken vermeld in dit proefschrift, was dat men vrijwel foutloos moest werken. Deze eis was niet onredelijk, aangezien de moeilijkheidsgraad van de items (of stimuli) van de taken zeer laag was. Een voorbeeld van een van de gebruikte taken is de Bourdon taak. De stimuli van deze taak bestonden uit patronen met drie, vier of vijf puntjes. De proefpersoon moest voor elke gepresenteerde stimulus aangeven of er vier (JA) danwel drie of vijf (NEE) puntjes aanwezig waren. De lengte van de taak bedroeg meestal 240 stimulus aanbiedingen afgezien van de oefentrials. Er werd een reactietijd (RT) geregistreerd per respons.

De moeilijkheid van het maken van een dergelijke taak bestaat niet in het geven van een juiste respons per stimulus aanbieding, maar in het vasthouden van de respons-snelheid, wanneer er ononderbroken stimuli worden aangeboden. De geobserveerde RT serie blijkt namelijk op te lopen. In hoofdstuk 2 wordt een overzicht gegeven van de literatuur op het terrein van de experimentele psychologie, waarin dit verschijnsel van prestatie verslechtering bij toenemende tijd herhaaldelijk is waargenomen. Deze achteruitgang in prestatie werd gevonden voor verschillende variabelen, zoals fouten percentage, waarnemingsgevoeligheid en RT, op uiteenlopende mentale taken, zoals seriële RT taken, vigilantie taken en repetitieve twee- (of meer-) keuze RT taken. Er bestaan twee of drie verschillende verklaringen voor dit verschijnsel: (1) verlies van aandachtscapaciteit, (2) inhibitie en (3) arousal. De inhibitie theorie wordt in dit proefschrift uitgewerkt.

De basis assumptie van de inhibitie theorie is dat de geobserveerde RT meer bevat dat alleen de tijd om de taak te verwerken (de procestijd). Deze resterende

tijd wordt distractietijd genoemd. Distractietijd omvat alle tijd die besteed wordt aan taak irrelevante mentale activiteiten. Verder wordt de assumptie gemaakt dat de waarschijnlijkheid (hazard rate) van een distractie periode, oftewel de 'inhibitie' van de taak, die verwerkt wordt, groter wordt met de procestijd. De inhibitie loopt dus op tijdens de procestijd, maar daalt weer tijdens een distractie periode. Dit inhibitie mechanisme is bepalend voor de voorspelling, dat bij onafgebroken werken aan een taak de RT stijgt. Het eerste doel van dit proefschrift is het toetsen van de inhibitie theorie.

In hoofdstuk 3 wordt de inhibitie theorie beschreven. Bovendien wordt aangegeven, op welke wijze toetsbare voorspellingen worden afgeleid uit de algemene theorie. Hiervoor wordt de zogenaamde wiskundige model benadering gekozen. De inhibitie theorie wordt omgezet in een wiskundig model, namelijk het INHIBITIE model. Vanuit dit wiskundige model worden voorspellingen afgeleid in termen van model parameters. Een voorbeeld van een voorspelling van het INHIBITIE model is dat de variantie van RT stijgt met het trial nummer, dat wil zeggen met de toenemende tijd van werken. Verder wordt in dit hoofdstuk concreet aangegeven op welke manier de voorspellingen in de experimenten van dit proefschrift zullen worden getoetst. Er worden redenen genoemd waarom de voorspellingen niet in termen van model parameters worden getoetst, maar alleen maar in termen van RT variabelen, zoals de gemiddelde RT, de kortste RT en de variantie van RT.

In hoofdstuk 4 wordt de inhibitie theorie getoetst in het zogenaamde massed versus spaced paradigma. In de massed conditie worden de stimuli in een ononderbroken reeks aan de proefpersoon gepresenteerd. De theorie voorspelt dan onder meer een stijgende RT curve en een stijgende RT variantie. In de spaced conditie wordt om de vier (of zes) trials een rustperiode ingevoerd. Er wordt verondersteld, dat in deze pauzes de inhibitie daalt. De voorspelling voor de spaced conditie is dan, dat RT niet zal stijgen en dat ook de RT variantie niet zal stijgen. Anders gezegd, er wordt voorspeld dat de distractietijd in de massed conditie veel groter zal zijn dan in de spaced conditie. Al deze voorspellingen werden door de gevonden data van het experiment gerapporteerd in hoofdstuk 4 bevestigd.

Homogene taken versus afwisselende taken werden aangeboden in de drie experimenten, die gerapporteerd worden in hoofdstuk 5. Bij het afwisselen van twee (of meer) taken wordt verondersteld, dat het verwerken van de ene taak een rustperiode biedt aan de verwerkingseenheden (de mentale processoren) van de andere taak. Er wordt dus aangenomen dat de inhibitie van de ene taak af zal nemen als de andere uitgevoerd wordt. De voorspellingen voor het massed versus spaced paradigma gelden dan mutatis mutandis voor het homogene taak versus afwisselende taken paradigma. Er wordt dus voorspeld dat de RT meer zou stijgen bij een homogene taak, dat de RT variantie meer zou stijgen in de homogene taak conditie en dat, meer algemeen, de distractietijd groter zou zijn in de homogene taak conditie dan in een afwisselende taken conditie. Ook deze voorspellingen werden door de data ondersteund.

In hoofdstuk 6 werd de lijn van de afwisselende taak conditie nog iets verder door getrokken. Indien namelijk twee taken gebruik maken van dezelfde mentale processoren, dan kan de inhibitie, die een mentale processor opbouwt niet (voldoende) worden afgebroken op het moment dat de tweede taak wordt uitgevoerd. In dit geval is er bij afwisseling van de taken dus meer sprake van een 'homogene' taak dan van een afwisselende taak. De voorspellingen voor een conditie, waarin twee taken worden afgewisseld, die dezelfde processoren gemeen hebben, komen dan ook overeen met de voorspellingen voor een homogene taak conditie: een stijgende RT, stijgende RT variantie en een relatief grote distractietijd. Wanneer we deze lijn van redeneren omdraaien, dan zou het vinden van een stijgende RT bij afwisseling van taken duiden op het overeenkomen van mentale processoren tussen twee taken. Het experiment van hoofdstuk 6 tendeert naar de conclusie dat het inderdaad mogelijk is om via dit paradigma gemeenschappelijke processoren op het spoor te komen.

Een tweede lijn van onderzoek binnen dit proefschrift is het ontwikkelen van een maat voor concentratie. In hoofdstuk 8 wordt uiteengezet hoe vanuit de inhibitie theorie een eenvoudige maat voor concentratie kan worden afgeleid. Deze maat geeft de verhouding weer tussen de procestijd en de distractietijd. Als de distractietijd klein is in verhouding tot de procestijd dan levert dit een grote waarde op voor concentratie, dat wil dus zeggen dat het concentratievermogen groot is. Deze theoretisch afgeleide maat blijkt in de experimentele en praktische toepassing redelijk tot goed te voldoen. Onder meer blijkt, dat deze concentratie maat redelijk ongevoelig is voor leereffecten, en dat de concentratie vrijwel onafhankelijk is van de mentale snelheid. Deze mentale snelheid wordt in dit proefschrift gedefiniëerd als de inverse van de procestijd. In hoofdstuk 7 wordt in het kort ingegaan op het begrip mentale snelheid, en op de relatie van dit begrip met intelligentie.

Hoofdstuk 9, tenslotte, geeft een evaluatie van de inhibitie theorie. Deze theorie blijkt empirisch beter te voldoen dan andere theorieën. Vooral de data, die werden gevonden in het homogene taken versus afwisselende taken paradigma kunnen moeilijk vanuit een andere theorie dan de inhibitie theorie worden verklaard.

Curriculum Vitae

Ronald Jansen wordt geboren op 17 augustus 1960 te Oldenzaal. Na het met succes afronden van de gymnasium-β opleiding aan het Carmellyceum te Oldenzaal, kiest hij in 1978 voor de universitaire studie Psychologie. Op grond van een bezwaarschrift wordt hij niet aan de V.U. in Amsterdam, maar aan de R.U. in Groningen geplaatst. Volgens schema behaalt hij in juni 1981 zijn kandidaats-examen en op 26 oktober 1984 studeert hij af als Persoonlijkheidspsycholoog. Tijdens de laatste jaren van zijn studie doet hij bestuurlijke ervaring op als lid van verschillende universitaire organen, waaronder de subfaculteitsraad en het dagelijks bestuur van zijn vakgroep. Wetenschappelijk gezien wordt hij gevormd in de school van prof. W.K.B. Hofstee. Zijn onderzoeksstages volbrengt hij onder begeleiding van prof. Ivo Molenaar, dr. Charlie Lewis, en dr. Wim Liebrand.

Vijf dagen na zijn afstuderen, op 1 november 1984, begint hij als junior wetenschappelijk medewerker bij de vakgroep Mathematische Psychologie aan de K.U. Nijmegen. Zijn onderzoekstaak bestaat uit het schrijven van een proefschrift op basis van het projectvoorstel getiteld 'Taakspecificiteit van Snelheid en Distractie bij simpele mentale taken'. Zijn leermeester in deze tijd is prof. Eddy Roskam. Verder is dr. Ad van der Ven als begeleider bij het project betrokken. Naast dit onderzoek geeft hij in al de vijf jaren dat hij verbonden is aan deze vakgroep, regelmatig doctoraal cursussen, waaronder Experimentele Designs, Quasi-experimentele Designs, en Methoden en Technieken voor Neuro- en Revalidatiepsychologie.

Sinds 1 januari 1990 werkt hij als 'ervaren onderzoeker' op het NWO aandachtsgebied 'Sociale Categorisatie en Attitude Verandering'. Dit project staat onder leiding van prof. Ad van Knippenberg en wordt gedeeltelijk aan de UvA (Amsterdam) en aan de R.U. Leiden, maar grotendeels aan de K.U. Nijmegen uitgevoerd bij de vakgroep Sociale Psychologie.

Stellingen

1. Het decomponeren van reactietijden op mentale taken in effectieve werktijd (procestijd) en ineffectieve werktijd (distractietijd) is nuttig als uitgangspunt voor het verklaren van verschijnselen als 'aandachtsverslapping', 'concentratieverlies' en 'snel afgeleid zijn'. *(Dit proefschrift).*

2. Indien toetsing van predicties niet leidt tot conclusies, die voor of tegen de theorie spreken, dan is dit euvel veelal te wijten aan een gebrek aan formalisatie van de theorie. *(Dit proefschrift).*

3. De meerwaarde van de concentratiemaat C boven de gangbare maten in bestaande concentratietests is, dat aan C een psychologische theorie ten grondslag ligt. *(Dit proefschrift).*

4. Verlies van aandachtscapaciteit voldoet niet als verklaringsprincipe voor de achteruitgang in prestaties op continue mentale taken, gezien de prestatie-verbetering bij (meer aandacht vragende) afwisseling van taken. *(Dit proefschrift).*

5. De verdeling van universitaire middelen over vakgroepen is een goed empirisch voorbeeld van een sequentiëel sociaal dilemma. Ook in dit geval blijkt coöperatief gedrag allengs plaats te maken voor het individualistische keuze gedrag, zoals al in de spelsituatie gevonden was door Liebrand, Jansen, Suhre & Rijken (1986). Het overlevingsprincipe wint het hierbij van het rechtvaardigheidsprincipe.

Liebrand, W., Jansen, R., Suhre, C. & Rijken, V. (1986). Might over Morality: Social Values and the Perception of Other Players in Experimental Games. *Journal of Experimental Social Psychology,* 22, 203-215.

6. Voor het toetsen van de voorspellingskracht van de meta-contrast ratio (MCR) met betrekking tot polarisatie van groepsstandpunten moet niet de samenhang tussen het standpunt met de hoogste MCR (per groep) op de voormeting en het groepsstandpunt op de nameting worden bekeken, zoals was voorgesteld door Meertens en Bähler (1989), maar moet de samenhang tussen het standpunt met de hoogste voormetings-MCR en de verschuiving van het groepsstandpunt (van voormeting naar nameting) onder de loep worden genomen. De correlatie, die berekend wordt door Meertens en Bähler, wordt voor het merendeel bepaald door de verdeeldheid in standpunten tussen de deelnemende groepjes.

Meertens, R. & Bähler, M. (1989). Referentie-informationele invloed en groepspolarisatie. In: Poppe, M., Extra, J., Knippenberg, A. van, Kok, G. & Seydel, E. (Eds.) *Fundamentele sociale psychologie, deel 3,* pp.131-146.

7. Indien men een stijgende (of dalende) trend met een univariate ANOVA wenst te toetsen, dient men in het algemeen geen lineaire of hogere orde contrasten te gebruiken, maar Helmert contrasten, aangezien in de meeste gevallen de eenheden van de factor, waarover de trend berekend wordt, niet aan het interval meetniveau voldoen. Helmert contrasten zijn orthogonaal en hebben als structuur: de eerste cel tegenover het gemiddelde van de tweede tot en met de laatste cel, vervolgens de tweede cel tegenover het gemiddelde van de derde tot en met de laatste, enzovoorts.

8. De procedure MANOVA SPSSX, Release 2.1, berekent voor de mixed model aansturing van een univariate ANOVA met herhaalde metingen en ongelijke celaantallen een foutieve kwadratensom voor de tussenproefpersonen factor.

9. Ook in het geval van studieduur verkorting mag binnen de sociale wetenschappen de tijd, die nodig is voor onderwijs in de methoden en technieken, niet worden ingekort, omdat het presenteren van foutief berekende resultaten en daaraan gekoppelde conclusies in onderzoeken, die tijdens of na de studie uitgevoerd worden, vele malen erger is dan helemaal geen onderzoek doen.

10. Nauwkeurige kansverdelingen voor de levensverwachting van mensen kunnen we in de nabije toekomst wel opstellen, maar we zullen nooit het fundamentele ethische probleem oplossen, waarom de ene mens meer in aanmerking komt voor een harttransplantatie dan een ander mens.

11. Onderzoek doen zonder vooraf het onderscheidingsvermogen van de gebruikte toetsen te bepalen komt overeen met het schieten op een schijf, waarbij we niet weten of de schijf op één meter, op tien meter, of op meer dan één kilometer van ons verwijderd staat.

12. Het zijn vooral de ex-rokers, die teren op de uitlaatgassen van rokers.

13. Elk proefschrift bevat minstens één typographische fout. *(Dit proefschrift).*

Stellingen behorende bij het proefschrift van Ronald Jansen,
Mental Speed and Concentration, Nijmegen, 15 mei 1990.

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